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REAL IMAGE VISUAL DISPLAY SYSTEM

THESIS

James R. Brandt
Captain, USAF

AFIT/GEO/ENG/92D-03

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REAL IMAGE VISUAL DISPLAY SYSTEM

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Electrical Engineering

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December, 1992

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James R. Brandt

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Abstract

This thesis investigates a technique for improving the perception of three-dimensionality in images generated by a Silicon Graphics workstation. The technique involves using a spherical mirror into which the graphics from the CRT are projected. A real image of the graphic is formed by the mirror and it appears to be floating at the image plane. The three-dimensional effect is improved by adding reflections or shadows of the displayed object. Additionally, a method of using real objects with computer generated shadows and computer generated objects with real shadows is investigated. This is done in an effort to quantify how far the real world can be integrated with the display as well as to show that the three-dimensionality of the original graphic is enhanced. The optical system is analyzed to show where the images are being formed and to determine the aberrations present in the system. The most noticeable image degradation is due to curvature of field. An improved optical system is proposed that would reduce this effect and increase the size of the display. Finally, this optical device along with the graphic techniques are integrated with two other research efforts. The first integration involves research in binaural sound and focuses on coupling visual and aural cues to create a pseudo synthetic environment. The second integration effort introduces battlefield terrain images into the optical device to enhance the images and functions as a C^3I display.

REAL IMAGE VISUAL DISPLAY SYSTEM

I. Introduction

1.1 Background

Creating realistic images of three-dimensional scenes has been a long term quest of researchers in the field of computer graphics. Defining what is a realistic picture and how much realism is needed is widely debated. A realistic picture runs the continuum from a true three-dimensional scene with real world richness of color, texture, lighting, and shadows; to images with significantly fewer visual cues such as a one-dimensional line drawing. Taking visual reality one step further by incorporating all sensory information yields what Naimark calls "realspace imaging".

> "Realspace imaging is the process of recording and displaying sensory information indistinguishable from unmediated reality. Imagine looking at a framed image as if it were a window. Fooling the eye into believing the image is real is a difficult task. Fooling two eyes is even more difficult. Fooling two eyes while allowing freedom of head motion is yet more difficult. Now imagine removing the frame and having the freedom to look around. Now imagine having the freedom to move around. Now add time based phenomena such as motion and sound. These are the elements of realspace imaging proposed (22)."

How much realism is needed depends on the task. A lot of time, money, and computer resource can be used developing a realistic image of a building for an architect when three simple orthographic views are sufficient. The military performs several tasks that would benefit from improved visual realism. Among them are flight simulation, modeling, command and control, and remote sensing.

This thesis investigates a display for improving visual realism. In the area of displays there are several types that are used to generate three-dimensional images. They fall broadly into three categories; holography, stereoscopic displays, and monoscopic displays.

Holography uses a coherent source (laser) to record on film the phase and amplitude of the light reflected off an object. Using the same laser to illuminate the film a three-dimensional image of the recorded object is formed (15).

Stereoscopic imaging presents two separate views of an object on a screen. One method of separating the images is to project the two views with different polarizations, one view is horizontally polarized and the other view is vertically polarized. Special glasses then separate the views so that the right eye receives one view and the left eye receives the other. The brain then combines the two images into a three-dimensional volume. Autostereoscopic imaging provides separate images of an object to each eye without the use of special glasses. One technique for doing this is given in detail in chapter two (6).

Monoscopic imaging projects a single view of the object from a computer screen. This is perhaps the most familiar technique and relies heavily on depth cues to produce images with three-dimensional perspective. A Silicon Graphics workstation is an example of a monoscopic display that provides three-dimensional realism in its graphics.

Capt Echeverry in his thesis "Real Imagery as a Three-Dimensional Display" (4) used lenses and parabolic mirrors to project an object from a CRT to a viewer. The resulting image appeared to be floating in space above the parabolic mirrors. This floating image effect added to the three-dimensional perception of the computer generated object. The advantages of Echeverry's work are that non-coherent sources such as a CRT can be used to generate the objects, special viewing glasses are not required, and real time imaging is possible. Additionally, Echeverry's display is scal-

able so that it could have a larger field of view and a larger exit pupil giving it multiuser capability.

This type of display is well suited for flight simulators as it would just be a matter of coupling the current computer driven graphics of a simulator with the appropriate optics. This would enhance the graphics of a standard flight simulator by bringing the scene off the screen. This display would also be good for a C^3I display in which sections of the battlefield are projected through the display from a database of terrain maps or actual pictures. The commander could see the terrain and interact with it by placing and moving various assets on the terrain. Finally, in the area of virtual reality or real space imaging, binaural recordings could be added that correspond to the visual scene and a data glove could be integrated into the system to allow the user to interact with the display. This would be an excellent research tool for studying virtual realities as it incorporates three of the senses (sight, sound and touch).

1.2 Problem Statement

This research focuses on improving the three-dimensional representation of objects displayed within the two-dimensional bounds of a computer screen through the use of optical elements. The optical elements will project to the viewer as a real image, a computer generated, three-dimensional object. The improvement will be assessed by comparing the image to the same image generated on a Silicon Graphics workstation and by comparing the results with the results obtained in previous research done in this area.

1.3 Scope

This thesis is a continuation of the research conducted by Capt Juan Echeverry and is intended to extend the methods he developed and introduce some new capabilities. Echeverry demonstrated in his work that a three-dimensional computer

generated image is enhanced by projecting that image through a parabolic mirror (4). The parabolic mirror focused the image in a plane above the mirror making the image to appear to be floating above the mirror. The main goals of this research are:

- increase the field of view so that multiple viewers can use the display
- introduce a reflected image to the graphic to improve the floating effect
- investigate other techniques to improve the floating effect
- introduce motion to the graphic and coordinate a reflection or shadow of the graphic with the motion
- analysis of the optics system including aberrations in the optical system, scalability of the display, and a proposal for the design of the next generation system
- integrate binaural sound with the display
- integrate a terrain map with the display

1.4 Methodology

Echeverry discussed an optical display device made by SEGA that incorporated a parabolic mirror technique similar to the one he used. The main difference is that SEGA's device has a much larger mirror than the parabolic projector used by Echeverry. This thesis uses the mirror from SEGA's device. Since this is a larger optic the exit pupil of the system is increased so that multiple viewers can view the display. With the larger optics, a larger CRT is brought into the system and therefore the system's field of view is increased.

The CRT is driven by a Silicon Graphics workstation. This allows a variety of graphic techniques to be experimented with to see what techniques enhance the three-dimensional effect when viewed through the optical device. The floating effect,

discussed by Echeverry, was key to perceiving a three-dimensional image (4). To enhance this effect a graphic is generated along with a reflected view of this graphic. The idea is that the reflected view is referenced to a horizontal plane at the top of the mirror system thus forcing the actual image higher than the referenced plane, enhancing the floating effect. Other techniques investigated include creating an artificial ground plane for the shadows to be cast upon so that the objects cast shadows instead of reflections. Additionally, the effect of real objects with graphically generated shadows and graphically generated objects with real shadows is investigated to see how far the real world and graphic display can be integrated without losing its effectiveness. According to Foley, simple graphical models look extremely three-dimensional when they move in a realistic fashion (8). With this in mind, motion is added to the graphic model and coordinated with the reflection or shadow.

The optical system is analyzed to show where and how the image is being formed. The aberrations inherent in the system are investigated using CODE V, an optics evaluation program by Optical Research Associates. A proposal for the design of the next generation device is presented. This proposal discusses the scalability of the device with the emphasis on increasing the image size while minimizing the aberrations.

Finally, work being done by Capt Scarborough in the area of binaural sound and work done by Capt Earl in the area of terrain imaging is integrated with the optical display to demonstrate potential applications (25)(3).

1.5 Overview of Thesis

This thesis is broken down into the following chapters:

Chapter 2 discusses the current knowledge in the area of three-dimensional imaging. It begins with a discussion of the various graphical methods for presenting three-dimensional information within the two-dimensional bounds of a computer screen. Next, several techniques for creating three-dimensional images are presented.

These methods focus primarily on autostereoscopic methods of producing three-dimensional images. Finally, a discussion of the utility of a three-dimensional display is presented. This discussion lists technologies of interest to the USAF that would benefit from the use of a three-dimensional display.

Chapter 3 presents the methodology, results and analysis. This chapter begins with an analysis of the optical display device used in this research. This analysis includes the image formation, the optical parameters, and the aberrations present in the system. Using the results from the analysis of the current optical system a proposal for the next generation device is presented. It then turns to the graphics used to investigate the three-dimensional effects of images viewed on the optical display device. The graphic used, why it was used, and the results obtained are all presented.

Chapter 4 discusses the integration of the optical device with other research efforts going on at AFIT. The integration involves two separate research projects: one incorporates binaural sound with the display, and the other incorporates terrain maps with the display.

Chapter 5 concludes the thesis by summarizing the results obtained and providing some ideas for future research in this area.

II. Current Knowledge

2.1 Introduction

Realspace imaging as stated in chapter one encompasses several different technologies. Since the ultimate goal of realspace imaging is to display sensory information indistinguishable from unmediated reality (22), it must embrace all five senses; sight, sound, touch, smell, taste. As shown in Figure 1, realspace imaging is like looking out a window at a scene and being able to interact with it with all of your senses. Visual realism on the other hand would be like looking at a picture of the same scene, sight is your only feedback. A combination of graphic tools and display devices are used to create these visually real scenes. For the purposes of this thesis discussion will be limited to sight, providing visual realism. Capt Eric Scarborough's thesis investigates binaural sound. This technique could be used to bring realistic sound to a virtual reality display (25).

Achieving visual realism involves both graphics techniques and display devices. The graphics techniques focus on how to map a three-dimensional object onto the two-dimensional bounds of the computer screen. Common techniques involve using perspective, shadows, lighting, and texture to give the viewer a sense of depth. The display device takes the graphic and presents it to the viewer. The most common displays are CRTs and projection screens. These displays present the graphic in the form of a single picture or a stereo pair. There are other display techniques such as holography that do not fit neatly into the above display description but are viable methods for achieving visual realism. This chapter will overview some of the graphics techniques used to achieve visual realism and then discuss several current display technologies.

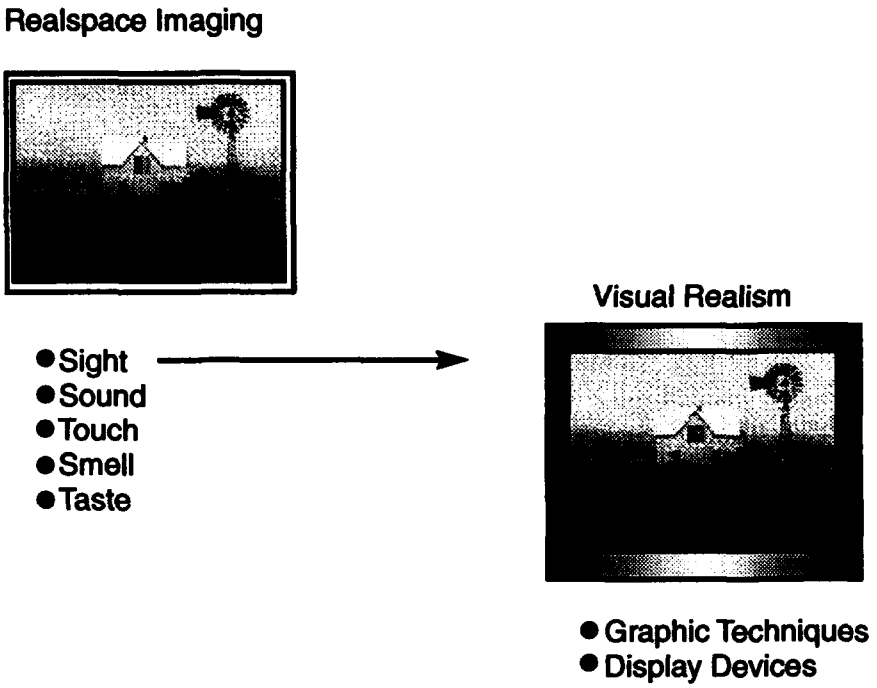


Figure 1. Realspace imaging block diagram

2.2 Graphic Techniques for Achieving Visual Realism

One problem with creating visual realism on a computer display is the difficulty of depicting spatial relationships. Most display devices are two dimensional, therefore three-dimensional objects must be projected into two-dimensional space. This loses information and creates ambiguities in the scene.

The Schröder stairway illusion, Figure 2 is an example of the ambiguities present in a two-dimensional scene. Is the stairway being viewed by looking down at the stairs or by looking up from underneath the stairs? The former interpretation is more likely since stairways are seen under our feet more often that over our head. In making this interpretation the viewer has formed a hypothesis. The more context the viewer has the more readily they will form a stable interpretation of the object. With a little imagination the other interpretation of the stairway can be visualized. However, with a blink of the eye the stairway will reverse itself for most viewers (8).

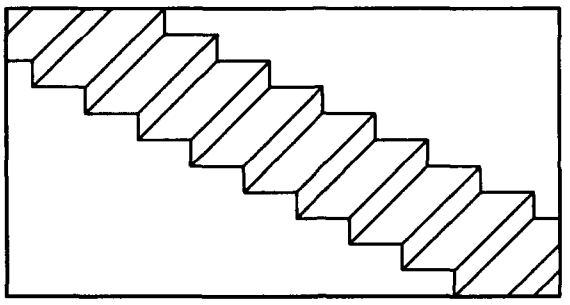


Figure 2. Schröder staircase (8)

To further illustrate the point Figure 3 shows the same staircase only this time with a person walking down the stairs. With this added context the correct interpretation

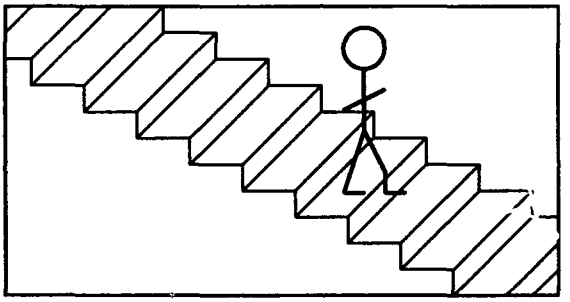


Figure 3. Schröder staircase with additional context

is obvious.

The graphic techniques discussed in this section attempt to add back that lost visual information so that the human depth perception mechanism can resolve the ambiguities. If successful then the perception is stable. The coordinate system used in this discussion and the rest of the document follows the coordinate system used by the Silicon Graphics display in its world coordinate system (7), see Figure 4.

Intensity: A sense of depth can be indicated by intensity. Lower intensity objects appear to be farther away. Intensity depth cueing interpolates the intensity of the object along a vector as a function of its starting and ending z coordinate

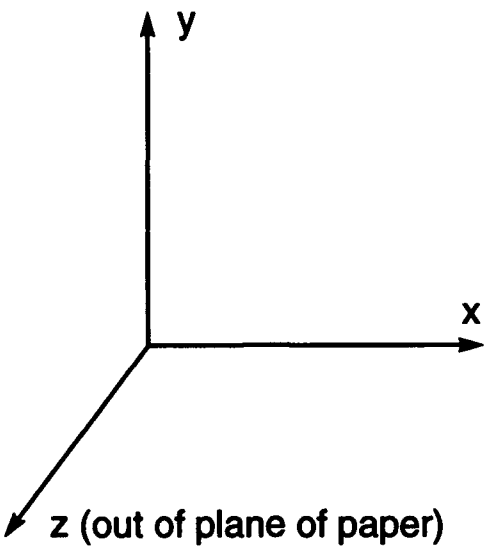


Figure 4. Coordinate system used throughout thesis

(the depth coordinate Figure 4). An object with depth would be most intense at the point closest to the viewer and linearly decrease in intensity to the point farthest from the viewer. Typically, a depth cue plane is set up parallel to the xy plane. The depth cue plane is moved up and down the z axis so that the viewer can restrict the depth being viewed. The intensity resolution of the human eye is lower than its spatial resolution so intensity depth cueing is not useful for accurately depicting small differences in distance. It is quite effective for determining large differences (8).

Aerial Perspective: To give the sense of even greater distance the intensity of an object is decreased and the image is less clearly defined (blurred). This gives the impression that the object is being viewed through a haze.

Shadows: A sense of depth is conveyed by shadows either attached to an object or cast on adjoining surfaces. If object A cast a shadow on surface B, then we know that A is between B and a light source (either direct or reflected). Furthermore, information on the type of light source can be determined from the shadow. A point

source such as a single light bulb cast sharp shadows, while an extended source such as the sun casts soft shadows.

Perspective: An object's size is scaled in inverse proportion to its distance from the viewer. Smaller objects are perceived as farther away. Perspective alone causes ambiguities as in the case of the object in Figure 5. If the viewer's hypothesis is that

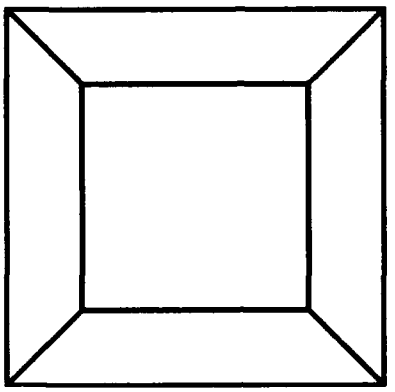


Figure 5. Perspective drawing of a open box lying on its side (8)

this is an open box lying on its side, then the smaller rectangle is behind the larger one and perspective is working as stated. If however, the viewers hypothesis is that the object is a truncated pyramid then the small rectangle is in front of the larger rectangle. If the viewer knows that the projected objects have parallel lines then perspective further helps convey depth since parallel lines converge at a vanishing point (8). This suggests that convergence is a stronger depth cue than diminishing size.

Texture: This technique uses shading or cross hatching to follow the shape of an object in order to delineate it more clearly. This provides cues as to the slant of a surface. When texture is coupled with perspective more lines are added whose convergence and foreshortening provide useful depth cues (8).

Highlighting: The particular reflection off of a curved surface conveys a sense of its three-dimensional nature. The type of reflection also conveys information

regarding the material properties of the object. If the object is dull the reflected light is dispersed in all direction with little glare. If the object is shiny the light is reflected intensely in a certain direction depending on the angle of incidence of the light.

Visible surface determination: This is also known as hidden surface removal, interposition, or occlusion. It simply means that the closer object obscures the contours of the more distant one. This conveys the spatial relationship between the objects.

Motion: The motion of an object relative to its previous position conveys a sense of its three-dimensionality by the changing texture, light and shadows along the surface of the object. As a three-dimensional object is rotated the viewer receives a series of different projections of the object. Figure 6 shows three different rotations of the Silicon Graphics logo. The different projections give the viewer a better understanding of what the entire object looks like. Additionally, under dynamic rotation, the maximum linear velocity of the points on the object near the center of rotation is lower than that of points further away from the center of rotation. This difference in velocity helps clarify relative distance of a point from the center. Finally, as an object rotates, the points on the object closer to the viewer appear larger than the points farther away. This changing perspective projection provides additional cues about the depth relationship (8). The larger the field of view the object occupies the more noticeable the effect is.

Foley suggests that motion may be even more powerful as a depth cue when under interactive control of the viewer. By selectively transforming an object the viewer forms a hypothesis about what the object is more quickly (8).

Stereopsis: This technique takes advantage of binocular disparity which refers to the disparity in the image cast by the same object, as viewed by two different eyes. Two spatially different views of an object are displayed on the screen, one for each eye. Section 2.3 discusses several ways to separate the objects so that each

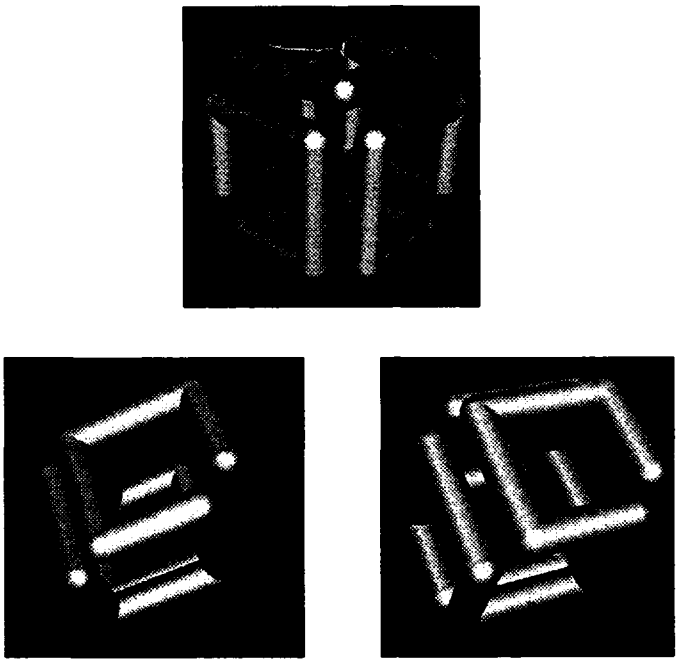


Figure 6. Three perspectives of Silicon Graphics logo

eye sees the appropriate view. Assuming that each eye is seeing the appropriate view, the brain takes these spatially different images and combines them into a three-dimensional volume.

Not all of the graphic cues must be present to create the three-dimensional perspective. In fact, binocular disparity, motion, and visible surface determination are the predominate cues from which the human sense interprets three-dimensionality (31). The art lies in choosing the correct cues to achieve a visually real effect.

2.3 Current Three-Dimensional Perspective Displays

Currently, displays providing three-dimensional perspective use either coherent (laser) light or incoherent (ordinary) light as its source. This thesis investigates a technique using incoherent light as its source, therefore only incoherent displays will

be discussed. The light source for these displays are generally cathode ray tubes (CRTs) and the displays are broadly categorized as stereoscopic or monoscopic.

2.3.1 Stereoscopic Displays Stereoscopic displays take advantage of binocular disparity as its primary depth cue. Spatially different views must be displayed to each eye. One technique for doing this is to use special glasses that present the appropriate view to each eye from a common display. A recent device that uses this technique is called CrystalEyes and was developed by the StereoGraphics Corporation (14). CrystalEyes is a pair of glasses with liquid crystal lenses and an infrared sensor in the center of the frame above the nose. The liquid crystal lenses act as shutters that are independently triggered. Two spatially different views are alternately displayed on a CRT. An infrared emitter is positioned at the display and transmits a synchronization signal to the IR sensor on the glasses. As the user views the display, the IR signal ensures that as the right eye view is being displayed at the screen, the right lens is open and vice versa. The shutters take 2.5 msec to open and 0.2 msec to close (14). This allows for flicker free viewing of three-dimensional objects. The disadvantage of this type of device is that you must wear the glasses to see the stereo image. This limits group viewing to the number of glasses available. Additionally, to avoid flicker the displays must be capable of operating at 120 fields per second. Although this is possible it does limit the display choice and increases cost.

Autostereoscopic displays take advantage of binocular disparity. However, they do not require the use of special glasses or any type of head mounted device for viewing. One such autostereoscopic device developed by Dimension Technologies is the DTI-100M. The DTI-100M uses a liquid crystal display in combination with a backlit illumination system (see Figure 7). The LCD(a) is placed in front of the illumination plate(b) which contains a number of thin vertical light emitting lines(c) across its surface. The LCD forms images by varying the transmissivity of each pixel(d) thus the light from the vertical lines is transmitted with varying intensity on a pixel by pixel basis. The lines are spaced apart so that the viewer's left eye(e)

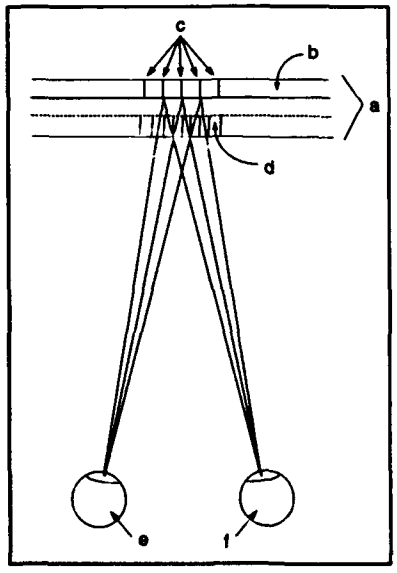


Figure 7. DTI-100M autostereoscopic display (5)—a) LCD, b) illumination plate, c) light emitting lines, d) pixel, e) left eye, f) right eye.

will see only lines through odd pixel columns and the viewer's right eye(f) will see only lines through even pixel columns. Thus, if the left eye view is displayed on the odd pixel columns and the right eye view is displayed on the even pixel columns, the viewer will see a stereoscopic image (5). There is a limited zone in front of the screen that the viewer can see the stereo images in. If the viewer is 30 inches from the front of the screen (optimal viewing distance) they can move side to side about 2.5 inches, back and forth about 18 inches and are unlimited in up and down movement (5).

The disadvantage of this system is the limited field of view. The viewer must stay within the prescribed box in order to see the stereo images. Although group viewing is possible, the group must be within the field of view, thus limiting the size of the group. Finally, the resolution of this display is cut in half since each eye sees only every other column of pixels (5).

Another autostereoscopic display involves using a lenticular screen for imaging. Lenticular screens are probably most familiar in the form of "3-D postcards" which

consist of an array of half cylindrical lenses. Multiplexed images depicting left and right eye views of a scene are placed behind the screen which match the screen pitch. The lenses refract the multiplexed images to the left and right eye forming a three-dimensional view. The advent of HDTV and high precision manufacturing techniques have made lenticular screens a viable option for autostereoscopic viewing. A lenticular sheet consists of a linear array of cylindrical lenses, each being a plano convex lens, see Figure 8. The lenticular sheet is transparent, the front face presents

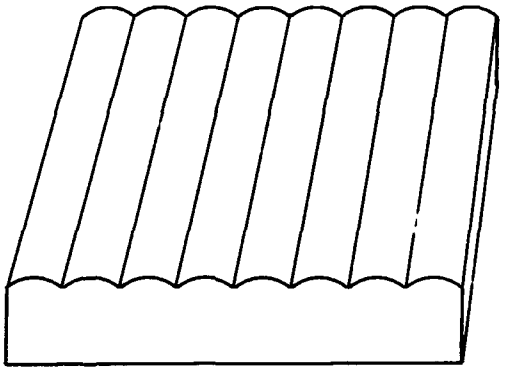


Figure 8. Lenticular screen

an array of grooves and the rear face, which constitutes the focal plane is flat. They have been widely used as projection screens for three-dimensional movies (19)(2)(13). More recently they have been considered for transmission screens. In this application a three-dimensional image displayed on a CRT is transmitted through the lenticular screen forming a three-dimensional view in front of the screen (12)(26)(13).

When used as a transmission screen the lenticular sheet is placed in front of the CRT or flat panel display so that the focal plane of the sheet is at the image plane of the display, see Figure 9. The sheet is positioned so that the lenses or grooves run parallel with the vertical columns of pixels on the display. Additionally, the pitch of the lenses is such that at least two pixels fall under each lens. The graphic on the display is generated so the odd pixel columns contain the left eye

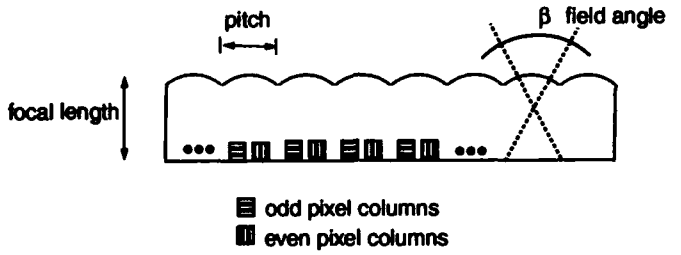


Figure 9. Lenticular screen parameters and pixel position (16)

view, and even pixel columns contain the right eye view as illustrated in Figure 10. Once the screen is properly aligned, the light from the pixels is refracted by the lens towards a viewing plane. At the viewing plane the odd pixel columns have separated from the even pixel columns by the interocculary distance (IOD) (6.5 cm for the average adult). A viewer in the correct position then receives a right eye view and a left eye view and can form a three-dimensional view from these. The viewing plane is based on the pitch of the lenticular screen, the focal length and the field angle, see Figure 9. Although the viewer must stay within a viewing area for three-dimensional viewing there are several such areas in front of the screen that afford a three-dimensional view, see Figure 11. NHK Science and Technical Research Laboratories have developed a 50 inch three-dimensional TV display system using a HDTV and lenticular sheet (12). Their system, shown in Figure 12, uses four color TV cameras and a high resolution LCD video projector. Images are recorded by the four cameras, multiplexed pixel by pixel to form a vertical stripe image which is then projected by the LCD video projector to the lenticular sheet. Four pixels are under each lens of the screen. This gives the system more viewing locations and more of a look around effect as the viewer goes from one viewing zone to the next, as shown in Figure 12. The specifications for this display device are listed in Table 1.

2.3.2 Monoscopic Displays Monoscopic displays show a single view of an object. With these displays binocular disparity is impossible, therefore; they rely

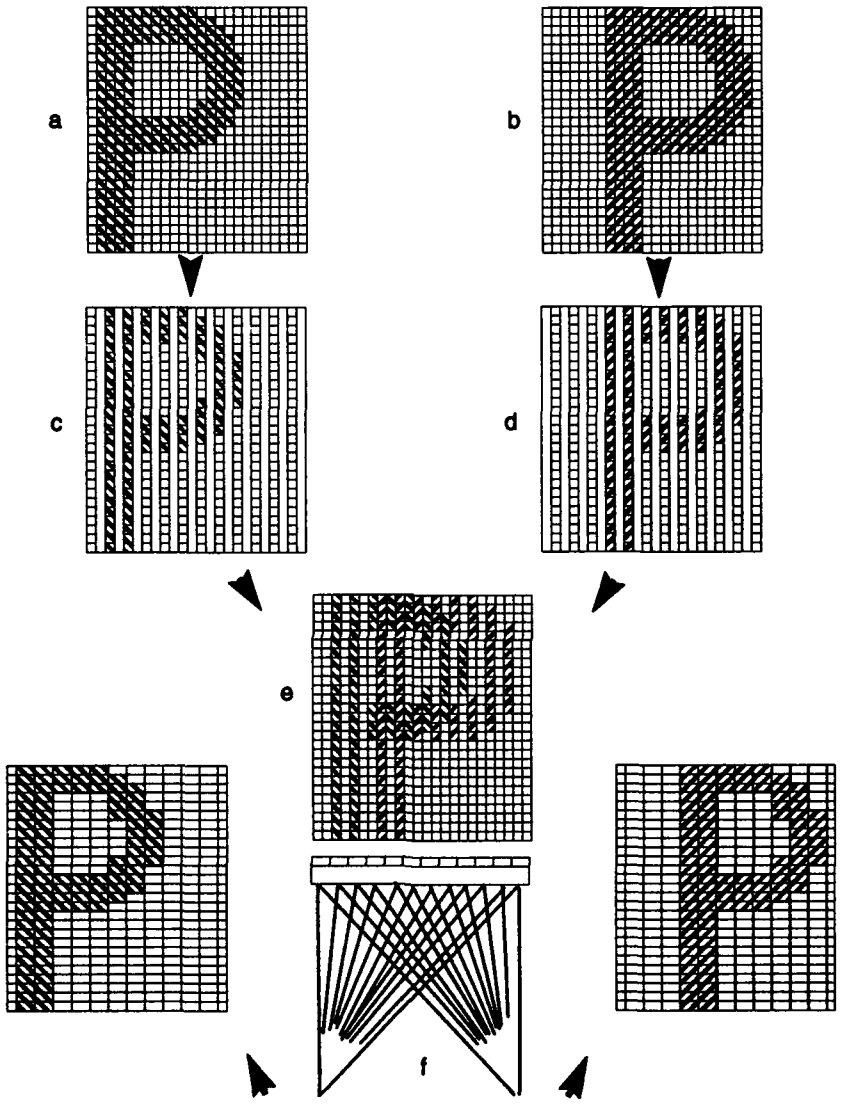


Figure 10. General viewing of a stereoscopic couple (9)— a and b) original left and right (256x256) pictures; c and d) useful parts (128x256) of the left and right picture; e) the (256x256) interleaved picture; f) lenticular screen and left/right viewed picture.

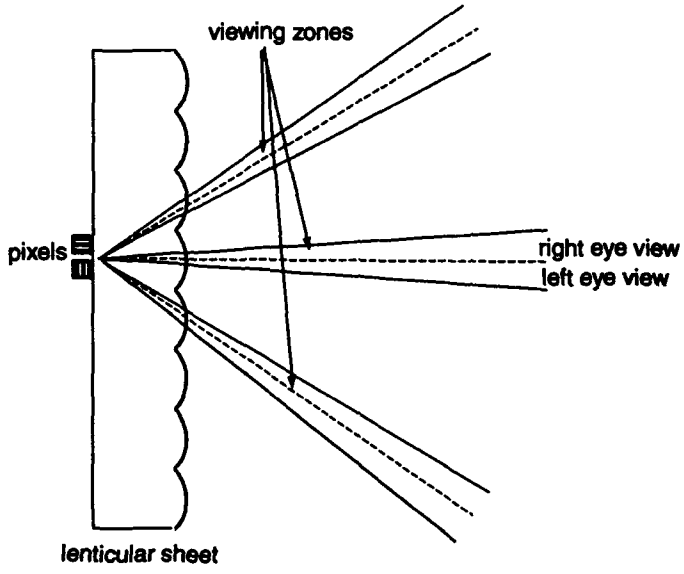


Figure 11. Viewing zones for lenticular screen (16)

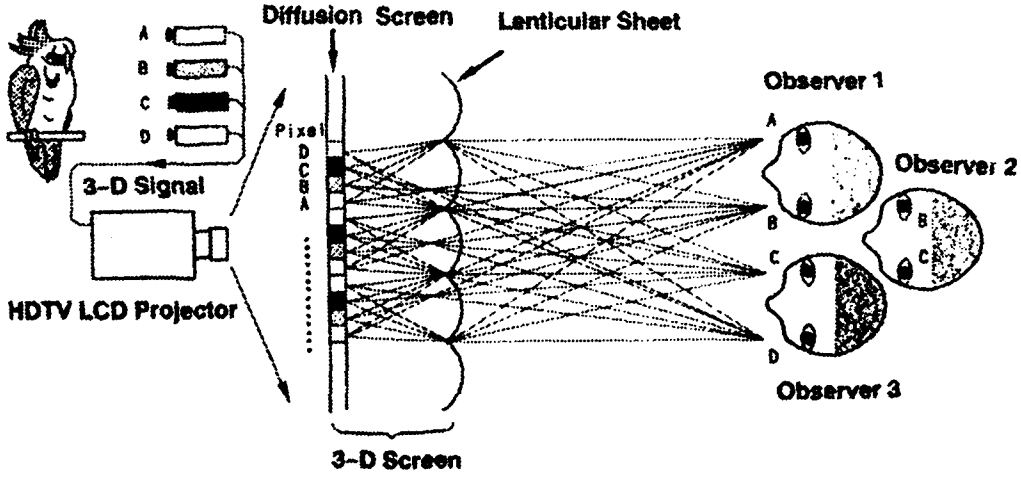


Figure 12. NHK's 3-D display system (12)

Table 1. Specifications for NHK's 3-D display system (12)

Parameters	Specification
Display Method	LCD Rear-Projection System
Display Image	Four Channels Full-Color 3-D Images
Screen Size	50-inch (Aspect Ratio 16:9)
LCD panel	5.5-inch, a-Si TFT Active Matrix Panel 1,474,560 (1440 x 1024) pixels x 3(RGB)
3-D Screen	Lenticular Screen (pitch 3.25 mm)
Luminance	350 cd/m^2
Contrast Ratio	130:1

heavily on the depth cues that allow depth to be mapped into the two-dimensional bounds of the display. The Silicon Graphics workstation is just one example of a monoscopic display. Through the use of depth cues these workstations provide very real, high resolution, three-dimensional perspective. Another example of a monoscopic display is the varifocal mirror. By dynamically changing the focal length of the mirror between two focal lengths the image from the mirror appears focused at a continuum of focal points between the two limits. The eye integrates the images into an apparent volume (29).

Another monoscopic display which uses mirrors was researched by Capt Juan Echeverry and described in his thesis, "Real Imagery as a Three-Dimensional Display" (4). Echeverry used a parabolic projector and a small CRT display to generate images that appeared to be floating in space. The parabolic projector consisted of two spherical mirrors joined together so that their reflective surfaces faced inward. A small hole in the top and bottom surfaces of the projector allowed light from a CRT to enter the bottom device and the image of the CRT to be viewed at the top of the device. The experimental set-up is shown in Figure 13. The image viewed through the top hole appeared to be floating much like a hologram would, providing an illusion of a three-dimensional stereo image (4). The disadvantage of this system

was the limited field of view and the small size of the images. These disadvantages were primarily due to the small optical elements used in the experiment.

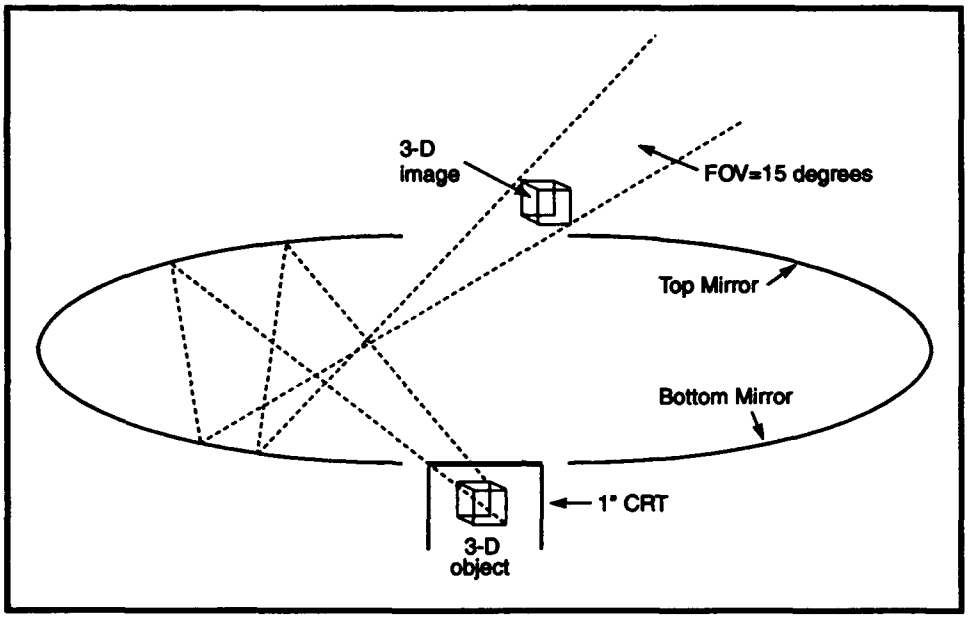


Figure 13. Parabolic projector (4)

2.4 Utility of Three-Dimensional Displays

In determining the overall utility of three-dimensional displays the following questions arise. Do three-dimensional stereoscopic displays provide a user with more depth information than do monoscopic displays? If they do, do they improve task performance? Most of the research done to answer these questions has been task specific (1). The tasks were things like viewing three-dimensional objects, interactive cursor positioning, simulation, and modeling. The researchers looked at one specific task to see if a three-dimensional stereoscopic display would improve the user's performance in this task. Although this provides useful information for that specific task it does not answer the broader question of what is the overall utility

of three-dimensional imaging. However, there are some common advantages and disadvantages resulting from this task specific research.

2.4.1 Advantages of Three-Dimensional Displays Researchers agree that three-dimensional stereoscopic displays provide more depth information. But, does this depth information improve performance in that task? Stereoscopic displays added significant value to applications which required viewing and interpreting complex, abstract, amorphous objects (30). This was especially true when the objects being viewed were unfamiliar to the viewer. The lack of a familiar concrete sense of what an object looks like enhances the three-dimensional stereo utility for the user. Stereoscopic displays also improved the users performance in tasks involving depth judgement in a three-dimensional space (32), manipulation of an object in three-dimensional space (1), comprehension of three-dimensional solids and in the identification of camouflaged objects (20). There are numerous tasks of interest to the USAF that meet the conditions mentioned above, including:

- simulations
- virtual reality
- remote sensing
- remote control of robots in hazardous areas
- complex data visualization
- modeling
- C^3I displays

Each of these tasks have different requirements for their three-dimensional display systems. The parabolic mirror technique discussed in this thesis is most beneficial for tasks requiring realtime, non precision feedback. This would include flight simulators, complex data visualization, C^3I displays, remote control of robots and as a research tool for virtual reality applications.

2.4.2 Disadvantages of Three-Dimensional Displays The quality of the image on a stereoscopic display is significantly worse than the quality of the image on monoscopic display. In many of the experiments comparing stereoscopic displays to monoscopic displays, the users cited that poor image was a major disadvantage in the stereoscopic displays (18) (32) (30). The image degradation problems include flicker, ghosting, and excessive parallax. Parallax is the difference in position of an object when viewed from one eye versus the other.

Another disadvantage is the need to wear special glasses for viewing the display in stereo (30). People generally work in groups and want their colleagues to be able to see and discuss the image being viewed all at one time. The need for group viewing is essential. Even though the autostereoscopic displays take care of the problem of having to wear glasses they still require the viewer to be within a small field of view (5). Other disadvantages that have been cited include cost, lack of portability of stereoscopic displays, eyestrain, and the need for greater computational resources (20) (30). Many of the disadvantages cited in this section will be solved as the technology matures.

2.5 Conclusions

In any task that requires a three-dimensional perspective display there are many depth cues that could be provided to the user. Giving the user everything, though possible, may not be needed. As Naimark said in his article on realspace imaging, "the trick is to give the sense of everything without giving everything." (22). The depth cue of binocular disparity, though providing true depth perception, suffers by giving poorer images, increased complexity, and increased cost. For some tasks binocular disparity is not needed. It is for these tasks that monoscopic displays could be used and the three-dimensional perspective in these displays improved. As was discussed in the advantages section, the USAF has many tasks that could benefit from three-dimensional displays. For any group viewing task, autostereoscopic

displays with a wide field of view is essential. Although the parabolic projector technique does not provide binocular disparity, it does provide a very real three-dimensional perspective and allows for group viewing. Additionally, the poor image problems of ghosting and parallax which are characteristics of three-dimensional stereoscopic displays are not a problem with the parabolic mirror technique. The limitations of this technique (field of view and poor resolution) can be improved by increasing the size of the optical elements. This device is well suited for use as a flight simulator display, C^3I display, or as a research tool in the area of virtual reality. This thesis investigates how to improve the three-dimensional images displayed on the parabolic projector. In particular what graphic techniques enhance the three-dimensional view and what can be done optically to improve the view.

Chapter 3 presents the methodology, results and analysis. The chapter begins with an analysis of the optical display device used in this research. This analysis includes the image formation, the optical parameters, and the aberrations present in the system. Using the results from the analysis of the current optical system a proposal for the next generation device is presented. Finally, the graphic used, why they were used and the results obtained are all presented.

III. Methodology, Results and Analysis

3.1 Introduction

This chapter begins with an analysis of the optical display device (ODD) used in this research. This analysis includes the image formation, the optical parameters, and the aberrations present in the system. Using the results from the analysis of the ODD a proposal for the next generation device is presented. It then turns to the graphics used to investigate the three dimensional effects of images viewed at the ODD. The graphic used, why it was used and the results obtained are all presented.

3.2 Analysis of the Optical Display Device

The ODD is contained within a video game called $TimeTraveler^{TM}$ by SEGA. It consists of a 20 inch color monitor, a large spherical mirror, and a glass viewing plane, see Figure 14. The object generated on the monitor is projected into the

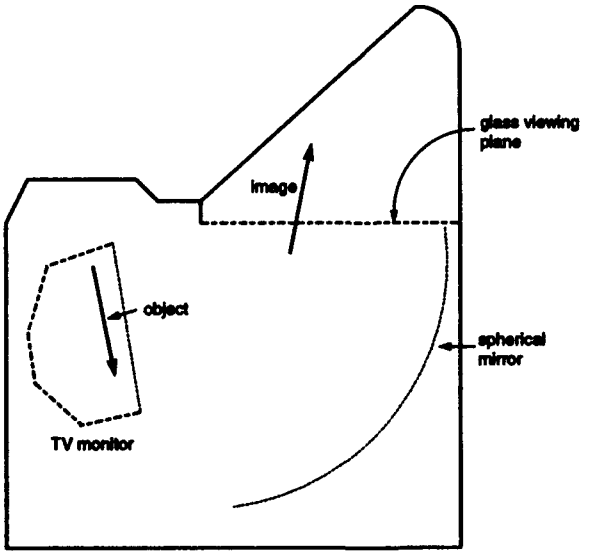


Figure 14. Optical display device

spherical mirror which reflects the energy from the monitor to form an image at the

glass viewing plane. The image at the glass appears to be standing on the glass. To understand where and how the image is formed the device was disassembled and analyzed.

3.2.1 Components of the ODD The spherical mirror is plastic. It is actually a quarter of a sphere. The manufacturing marks suggest that it was formed as a hemisphere and then cut in half. The radius of the sphere is 43 cm giving it a focal length of 21.5 cm. The back surface of the mirror is blackened with what appears to be a glossy black paint. This gives the mirror a very low reflectivity compared to a high quality silvered mirror which typically have a reflectivity greater than 90% (10). Power measurements made by reflecting a He-Ne laser off the blackened mirror showed that only 5% of the incident energy is reflected. This was puzzling at first until some of Echeverry's results were taken into account. The parabolic mirrors Echeverry used were silvered and therefore had a much higher reflectivity (4). Any objects that appeared in the line of sight between the object, mirror, and viewer were seen by the viewer. Since a CRT was used to generate the objects, the objects as well as the CRT casing were seen in the image plane. Echeverry found that with his device the illusion was spoiled by extra information such as the case of the CRT (4). By using a mirror with a much lower reflectivity, dimmer objects, in particular non-light emitting objects (such as the CRT case), are not seen in the reflected image. This preserves the illusion.

The orientation of the mirror and the monitor within the device is illustrated in Figure 15. The mirror is mounted at an angle of 7.5° with respect to normal. The monitor is mounted with a 9.1° angle with respect to normal. The optical axis intersects the monitor screen 4 cm down from the top. Due to the angular difference between the monitor and mirror the monitor is not perpendicular to the optical axis (the monitor is 88.4° with respect to the optical axis). This small deviation from perpendicular has no noticeable effect on the image and is probably a tolerance limitation in the manufacturing of the supports that hold the mirror and monitor.

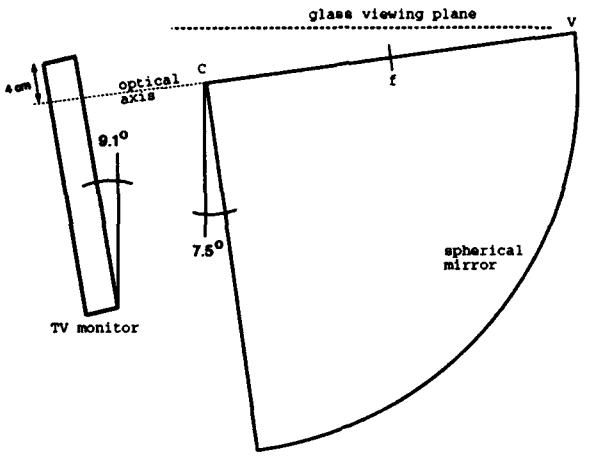


Figure 15. Orientation of mirror and monitor

Around the edge of the glass viewing surface there is an opaque mask as shown in Figure 16. This mask is part of the limiting aperture of the system. There are

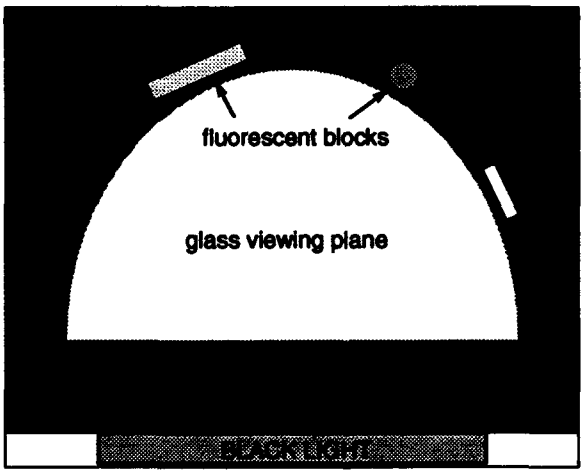


Figure 16. Glass viewing plane of optical display device

several small fluorescent blocks at the edge of the mask. These blocks are illuminated by a black light which is located in front of the blocks, above the glass but hidden from the viewer. When illuminated these blocks have an intense color and therefore, a very strong reflection off the glass. This reflection helps the viewer to psychologically

lock up the glass surface as the ground plane and therefore improves the illusion that the image is floating above the glass surface. It should be noted however, that the images will float with or without the presence of the blocks.

3.2.2 Image formation on the ODD The gaussian lens formula equation 1 was used to find where the images are formed in the ODD.

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f} \tag{1}$$

The terms s_o, s_i, and f are the distance from the object to the optical element, the distance from the image to the optical element, and the focal length of the optical element, respectively. When working with spherical mirrors and using the gaussian lens formula the following sign conventions are applicable, see Table 2. In this table V is the vertex of the mirror which is the point at which the optical axis intersect the mirror, C is the center of curvature, R is the radius of curvature of the mirror, y_o and y_i are the height of the object and image respectively. The other entries are as defined previously.

Table 2. Sign convention for spherical mirrors (10)

Quantity	Sign	
	+	-
s_o	Left of V, real object	Right of V, virtual object
s_i	Left of V, real image	Right of V, virtual image
f	Concave mirror	Convex mirror
R	C right of V, convex	C left of V, concave
y_o	Above axis, erect object	Below axis, inverted object
y_i	Above axis, erect image	Below axis, inverted image

For spherical mirrors, $f = -R/2$. Additionally, for concave mirrors, $|R| < 0$ and for convex mirrors $|R| > 0$, as shown in Table 2. The optical display device has

a concave spherical mirror with a radius of curvature equal to -43 cm. Therefore, the focal length is equal to 21.5 cm.

The image location is dependent on the objects location with respect to the focal point of the mirror. Table 3 shows the image type, where it is formed, its orientation, and size with respect to the object location.

Table 3. Images of real objects formed by spherical mirrors (10)

Concave				
Object	Image			
Location	Type	Location	Orientation	Relative Size
$\infty > s_o > 2f$	Real	$f < s_i < 2f$	Inverted	Minified
$s_o = 2f$	Real	$s_i = 2f$	Inverted	Same size
$f < s_o < 2f$	Real	$\infty > s_i > 2f$	Inverted	Magnified
$s_o = f$		$\pm\infty$		
$s_o < f$	Virtual	$\|s_i\| > s_o$	Erect	Magnified
Convex				
Object	Image			
Location	Type	Location	Orientation	Relative Size
Anywhere	Virtual	$\|s_i\| < \|f\|$, $s_o > \|s_i\|$	Erect	Minified

At the optical axis, s_o equals 60 cm (the distance from the CRT monitor to the vertex of the mirror). This is less than ∞ but greater than $2f$. Therefore, from Table 3 we expect a real, inverted, minified image located between f and $2f$. According to Equation 1, s_i equals 33.5 cm. By the sign convention established in Table 2 the image will be located 33.5 cm to the left of the vertex of the mirror. Magnification of an optical system is given by equation 2.

$$M = \frac{-s_i}{s_o} \tag{2}$$

Therefore, the magnification of this ODD is -0.558. The image is reduced and inverted, see Figure 17.

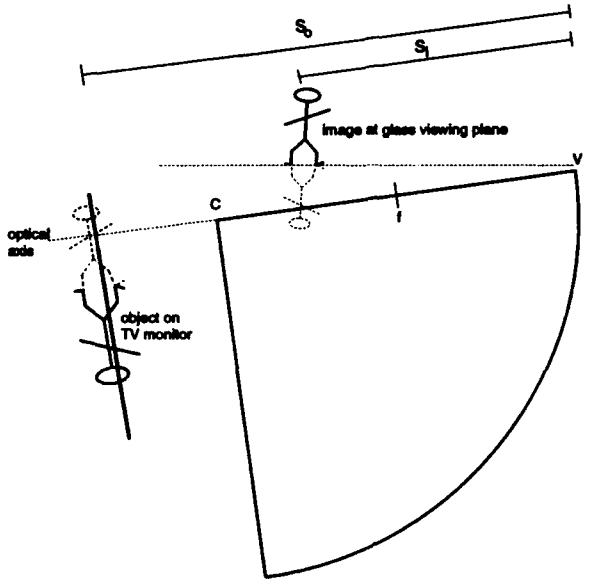


Figure 17. Location of image on optical display device

3.2.3 Graphics on the ODD The graphics generated on the monitor consist of an object and the object's reflection. The reflection is the mirrored and inverted view of the object as shown in Figure 17. The objects are rendered upside down on the monitor so that when the spherical mirror inverts them they will appear with the correct orientation to the viewer. There is an imaginary horizontal plane between the object and its reflection. This acts as the surface the object would be standing on. The object and reflection must stay on the appropriate side of this line to preserve the floating effect.

3.3 Optical Analysis

This section analyzes the optical system of the ODD. It begins by locating the aperture stops and various pupils, then determines the system's field of view,

the instantaneous field of view and concludes with the aberrations present in the system. The optics involved in the ODD consist simply of a spherical mirror and a glass viewing plane. This makes the location of the various stops trivial.

3.3.1 Stops and Field of View The aperture stop is the optical component which controls the size of the maximum cone of rays leaving an object point that can be processed by the entire optical system (23). For the ODD the mirror is the aperture stop.

The entrance pupil is the image of the aperture stop formed by the optical elements proceeding it (23). Since no elements proceed the aperture stop the mirror is also the entrance pupil.

The exit pupil is the image of the aperture stop formed by the optical elements following it (23). The only element following the aperture stop is the glass viewing plane. The viewing plane has an opaque mask on it as was seen in Figure 16 which does limit some of the energy reflected from the mirror. The mask is not symmetric with the mirror and only limits energy reflected from the far left and right sides of the mirror. It does not effect the energy reflected from the top and bottom of the mirror. Therefore the exit pupil is 43 cm vertically (same as the mirror) and 65 cm horizontally (due to the mask). In comparison, Echeverry's display had a 6 cm diameter exit pupil. The observers eye must remain within the area projected by the exit pupil to permit viewing. The larger the exit pupil the more the viewer can move around and still see the entire image. The large exit pupil on the ODD gives the viewer a 73° horizontal viewing window in front of the display, as compared to a 15° window on Echeverry's display. A viewer can stand 55 cm to either side of the display and see the image. The further to the side one stands the more noticeable the aberrations discussed in Section 3.3.2 appear. Front and back head motion is fairly unconstrained. A viewer can back away from the display as far as he wants until the image is too small to see. Forward movement is limited by the effects of horizontal

parallax. If the viewer gets closer than approximately 40 cm from the vertex of the mirror the horizontal parallax is to great to adequately fuse the images. By closing one eye and viewing the display a clear view is once again seen. In comparison, Echeverry's display had a minimum viewing distance of 20 cm but the lateral head movement was limited to 2.5 cm side to side.

The field stop is the aperture that controls the field of view and is similarly the mirror. The field of view is the lateral extent of the object that is imaged or can be seen through the optical system. The angular field of view (FOV) is the angle subtended at the vertex of the mirror by the monitor. Typically the FOV is symmetric about the optical axis and is reported as a single angular number that is understood to be plus or minus that angle. For the ODD, the monitor is not centered on the optical axis so the FOV is reported in a slightly different form. The size of the monitor is 30 cm high and 40 cm wide and is obviously what limits the size of the object. This yields a total vertical FOV of 27.2° and a total horizontal FOV is 36.86°. It is important to note that this is the angular FOV of the system(angle subtended by the mirror at the monitor), this differs from the FOV presented to the viewer. The FOV presented to the viewer is referred to as the instantaneous FOV and is the angle subtended at the eye by the image displayed on the ODD. This is a more useful measurement for comparing the this system to other virtual reality systems, especially helmet mounted display systems. The instantaneous FOV for a 6 foot tall viewer standing directly in front of the ODD is ±6.06° horizontally and ±4.55° vertically. In comparison, the same viewer, observing the parabolic mirror display Echeverry used, has an instantaneous field of view of ±1.38°.

The importance of instantaneous FOV size depends on the task for which the device will be used. A true to life virtual reality application would require a FOV approaching that of the human visual system, approximately 200° horizontally and 120° vertically (21). On the other hand a visual feedback system for remote control of a robot may only require 10° FOV. In human visual tasks only the central 3° to 5°

provide high acuity vision, the visual acuity drops rapidly outside of that area. The extra FOV is important however for providing peripheral vision information (28).

A trade off with large FOV is image resolution. A CRT has a finite number of pixels, therefore, as the FOV increases these pixels are spread over a larger angular subtense per pixel which corresponds to lower angular resolution. This is not a problem with the analyzed configuration of the ODD since it has a fairly small instantaneous FOV.

3.3.2 Siedel Aberrations The aberrations in the ODD are primarily due to the off axis imaging. Typically the farther off the optical axis the object is the more the aberration effects the image quality due to the fact that it is no longer in the paraxial region. The aberrations investigated are limited to the third order Siedel Aberrations. This analysis was carried out using Code V, a software package designed to investigate optical systems. (Appendix C provides some tips for using Code V at AFIT.) The five Siedel aberrations are spherical, coma, astigmatism, field curvature and distortion. Explanation and derivation of these aberrations can be found in Pedrotti's book, *Introduction to Optics* (23). The terms which comprise the aberrations are as follows:

r^4	spherical aberration
$hr^3 cos\ \theta$	coma
$h^2r^2cos^2\ \theta$	astigmatism
h^2r^2	curvature of field
$h^3rcos\ \theta$	distortion

where r is the radial distance from the optical axis at the mirror to the point where the ray of interest intersects the mirror; h is the distance from the optical axis to where the point focuses; and θ is the angle r makes with a line normal to the optical axis at the vertex of the mirror, as shown in Figure 18. The net effect of these aberrations is image degradation. To improve image quality these aberrations must

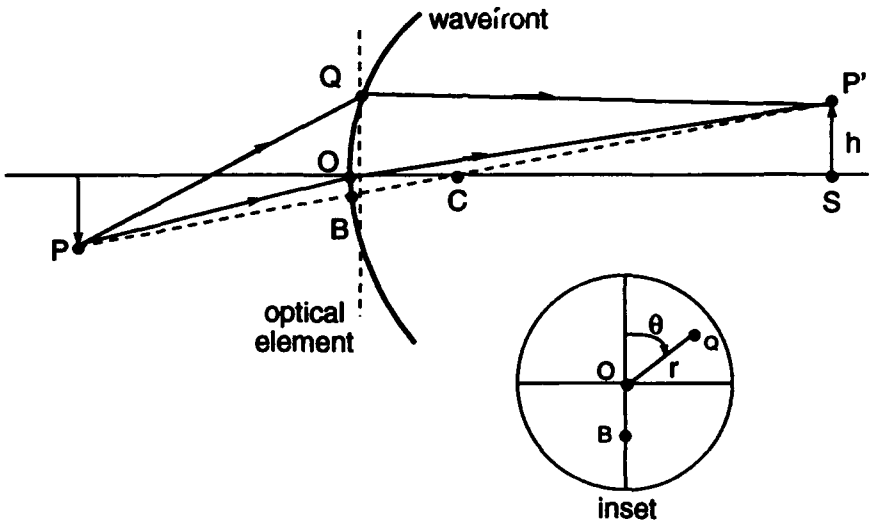


Figure 18. Points of interest in Siedel aberrations (23); inset shows the detail of the frontal view of a portion of the wavefront

be reduced. Other than spherical aberration, the value of the aberration is different for every object point. For analysis of the ODD the furthest point from the optical axis in the object plane (20,-25) was selected to get the values shown in Table 4. All entries are expressed in cm of maximum shift or blur on the image plane.

Table 4. Aberrations at the image plane due to a point at (20,-25) in the object plane

Spher	Coma	Tan Ast	Sag Ast	Petz	Petz Curv	Dist
-2.690	15.376	-19.532	0.000	9.766	0.047	0.000

Spherical aberration (SA) occurs on the ODD when rays from the outer zone of the concave mirror cross the axis inside the paraxial focus. The distance between the paraxial focus and the point at which the outer rays cross is the amount of spherical aberration. It shows itself by blurring the image. For a given optical set up the SA is the same for all points on and off the optical axis. It is the only Siedel

aberration that does not depend on h. SA depends on entrance pupil diameter and object distance.

Coma derives its name from the cometlike appearance of the image of an object located just off the axis. Coma is represented by the term $hr^3cos\theta$ which indicates an off axis aberration ($h \neq 0$), that is nonsymmetric about the optical axis ($cos\theta \neq$constant) and increases rapidly with aperture r.

Astigmatism and field curvature are closely related as evidence by their h^2 and r^2 dependence. Astigmatism is a defect in the image that occurs when an object point lies some distance from the axis of the concave mirror. This aberration increases with off axis distance of the object and with aperture. When the incident rays make an appreciable angle with the mirror axis the result is that instead of a point image, two mutually perpendicular line images are formed. Reflected rays in the tangential plane focus at a point t and the reflected rays in the sagital plane (perpendicular to the tangential plane) focus at a point s. In the ODD the sagital rays focus at the image plane therefore the sagital astigmatism is zero as shown in Table 4. If the tangential astigmatism values were calculated for every object point, a curved surface would be mapped out with its vertex at the center of the image plane. To eliminate astigmatism, the tangential and sagital surfaces (T and S) must coincide. When this is accomplished the resulting surface is called the Petzval surface (P). If this surface is curved, although astigmatism has been eliminated, an associated aberration called curvature of field remains. To record sharp images under these conditions, the film must be shaped to fit P. Even if T and S do not coincide as in the case of the ODD, a Petzval surface can be determined mathematically. In third order theory, the PT and PS distance always maintains a 3:1 ratio. Additionally, the P surface always lies on the side of the S surface opposite the T surface. For the ODD, as shown in Table 4 the Petzval surface (Petz) is located 9.766 cm to the left of the image plane and has a curvature (Petz Curv) of 0.047 cm. It is important to note that the Petzval surface and curvature are purely mathematical treatments that

indicate how much the image field is curved. A flat Petzval surface would indicate no curvature of field. In general the Petzval condition for a number of optical elements is shown in Equation 3 where R_p is the radius of curvature of the Petzval surface.

$$\sum_{i=1}^{n} \frac{1}{n_i fi} = \frac{1}{R_p} \tag{3}$$

Making the surface flat, $R_p = 0$, for a single lens system, such as the ODD, is impossible. The image degradation effect however, can be reduced by placing an aperture in front of the mirror which would limit h and r.

Distortion is evidenced by a variation in the lateral magnification for object points at different distances from the optical axis. If the magnification increases with distance from the axis the result is pincushion distortion. If the magnification decreases with distance from the axis the result is barrel distortion. Distortion is caused by ray bundles being limited by aperture stops. If the aperture is on the object side of the lens the result is barrel distortion. If the aperture is on the image side of the lens the result is pincushion distortion. On the ODD the aperture stop is the mirror, the ray bundles are not limited, therefore no distortion is evident in the image. In the design proposal for the next generation device, Section 3.4, some distortion appears due to the fact that an aperture is added to reduce the effects of astigmatism.

Although some of these aberrations seem large (physical quantity) the visual effect is minimal when viewing the ODD. The most noticeable aberration in the display is curvature of field. The effect of field curvature is evident in comparing Figure 19 to Figure 20. Figure 19 is a grid pattern generated on the Silicon Graphics and output to the TV monitor on the ODD. Figure 20 is the grid pattern after being processed through the ODD.

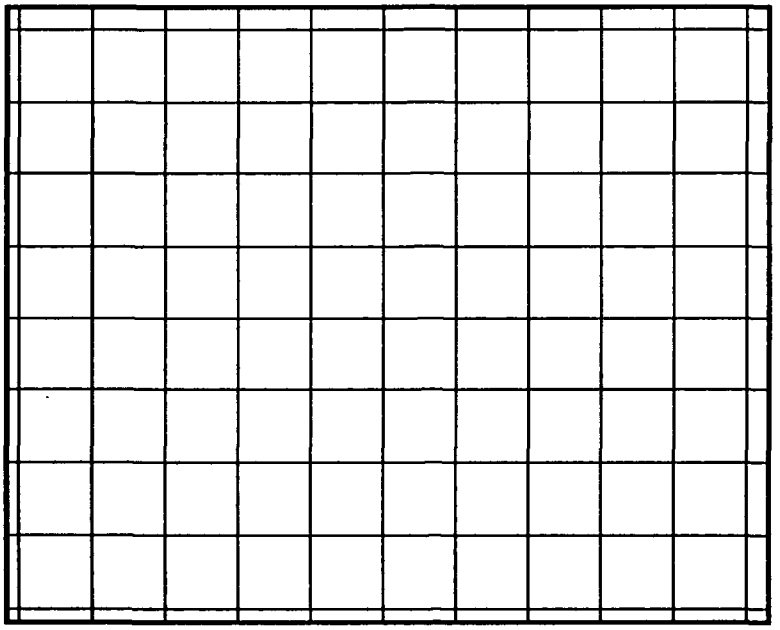


Figure 19. Grid pattern on TV monitor

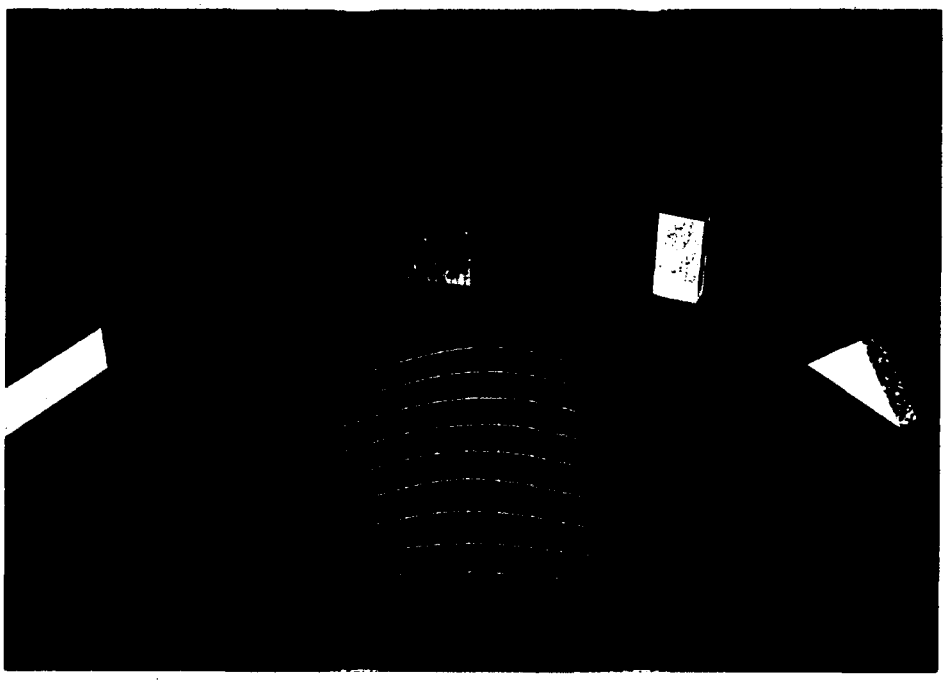


Figure 20. Grid pattern on ODD

3.4 Scalability and Design Proposal

This section addresses the scalability of the ODD and proposes a design for the next ODD. These issues are related and the analysis from the previous section is used here. The final design's aberrations will be compared to the aberrations listed in the previous section to quantify the improvement.

The analysis begins with the current ODD to see what parameters can be changed to increase the image size and improve image quality. Apertures will be added to the ODD to limit the aberrations caused by increasing the image size. The size and shape of the mirror will be changed so that the aberration associated with field curvature will be reduced. Finally, a design proposal for the next generation ODD will be presented. The scaled system is analyzed using Code V. Although a perfect aberration free system is possible it is not cost effective for this application. The goal is to scale the system without increasing the aberrations listed in Table 4 by more than 10 percent. This was chosen because even though the ODD has aberrations present the image was not noticeably degraded to the viewer. The one exception to this goal is field curvature (listed as Petz Curv in Table 4), since this was a noticeable aberration in the ODD it will not be allowed to increase in the scaled version.

The ODD currently is limited in that the viewer must look down into the device to see the image. As the viewer moves his view point lower (toward the optical axis), the image moves higher. Many of the people that viewed the ODD would do this to see if there really was an object floating above the viewing plane. The image would move higher until it reached the back edge of the mirror where it would fall off. By replacing the mirror currently in the ODD with a mirror which extends above the glass viewing plane, the display would be improved as this would allow the viewer to look directly down the optical axis and see the whole image above this axis, see Figure 21.

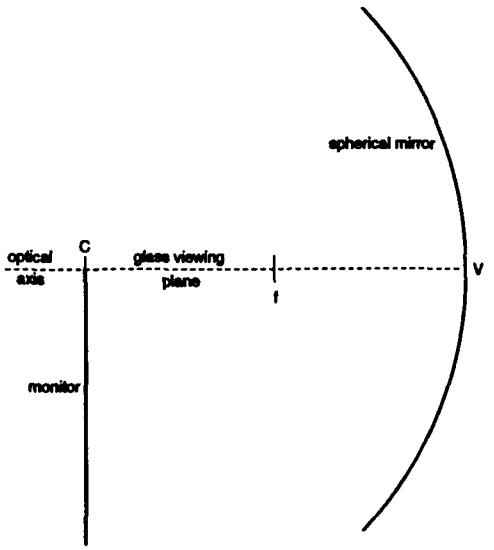


Figure 21. Scaled ODD

The output image of the ODD can obviously be increased by moving the CRT closer to the mirror. As was shown in Table 3 the image will be real as long as the CRT is positioned such that $\infty > s_o > f$, where s_o is the distance from the vertex of the mirror to the CRT. Additionally, if $2f > s_o > f$, the image will be magnified. The cost however is image degradation. The aberrations associated with coma and astigmatism become much worse. For example, if the CRT was positioned such that $s_o = 35cm$ the image would be magnified. According to Equation 1 the image is located 55.74 cm from the vertex of the mirror and from Equation 2 the image is 1.59 times larger. However, the tangential coma for the same point given in Table 4 is -35.67 cm (versus 15.376 cm) and the tangential astigmatism is -97.11 cm (versus -19.532 cm).

To decrease the amount of image blurring associated with the aberrations discussed above an aperture stop is introduced between the mirror and the CRT. The aperture stop limits the oblique rays of light which will reduce the amount of coma and astigmatism. If an aperture stop with a 60 cm diameter opening is placed immediately in front of the mirror, the coma and astigmatism are reduced to -17.36

cm and -67.75 cm respectively. Coma is within the design goal but the astigmatism is still too large. The aperture stop must be stopped down to a diameter of 19 cm before the astigmatism is within the design window. This decreases the exit pupil by 77 percent. Therefore, the number of people that can view the display at once is limited. The solution proposed is to sacrifice some magnification and move the monitor further away from the mirror. When $s_o = C$ spherical aberration and coma go to zero and the only aberration that needs to be reduced to meet the design goal is the tangential astigmatism. This can be accomplished with an aperture placed immediately in front of the mirror however, the aperture must be stopped down to 23 cm diameter to meet the design goal. Once again the exit pupil is reduced limiting the number of viewers. Increasing the radius of curvature of the mirror will help reduce the problem of astigmatism. This has an additional benefit of decreasing the amount of curvature of field. Curvature of field goes as $1/f$ so any increase in f will decrease this aberration. For this analysis a mirror with a radius of curvature of -60 cm is selected. This allows for a significant decrease in curvature of field and astigmatism yet keeps the mirror/CRT separation to the limits of the current ODD setup. The CRT is placed so that $s_o = 60$ cm and the aperture stop, placed immediately in front of the mirror, is opened up to a 73 cm diameter. Figure 21 is a picture of the scaled ODD, the effect of the aperture is to cut off the extent of the mirror so that it is not a full hemisphere. The aberrations associated with this set up are shown in Table 5, all are within the 10 percent design window except distortion (it

Table 5. Aberrations at the image plane due to a point at (20,-25) in the object plane

Spher	Coma	Tan Ast	Sag Ast	Petz	Petz Curv	Dist
0.000	0.000	-21.460	0.000	10.730	0.033	-0.158

was zero in the original ODD). The size of the image displayed has nearly doubled

since this design has a magnification of 1 compared to .558 for the original ODD. The instantaneous FOV (angle subtended at the eye to the display) is increased to $\pm 10.4°$ (versus $\pm 6.06°$ in the original configuration). Finally, the exit pupil has been increased vertically from 43 cm to 73 cm.

A trade off to a magnified image is resolution. The larger the magnification the less resolution at the image plane. For the original ODD setup the resolution is 42.6 pixels per degree horizontally. If the image size was doubled as in the scaled version discussed previously, the resolution would be 24.57 pixels per degree. This resolution is limited by the monitor in the ODD which is a standard TV format, 512×512 pixels. To reduce the loss of resolution as the display is scaled and image magnified, the Silicon Graphics monitor can be used instead of the TV monitor in the ODD. The TV monitor and Silicon Graphics monitor are the same size so image size will not change. The Silicon Graphics monitor has 1280×1044 pixels this would give a resolution of 106.6 pixels per degree for the original ODD and 61.44 pixels per degree for the scaled version.

If the magnification is kept at 1 as in the scaled ODD the only way to increase the size of the output image is to increase the size of the monitor. As monitors increase in size past the conventional CRT monitors the intensity per unit area produced by the monitor decreases. Although large screen TVs are improving, the light intensity is much less than a conventional CRT monitor. In the ODD as the intensity of the light decreases, the reflected images become washed out. To increase the size of the input object and maintain suitable light levels a CRT projector can be used. A CRT projector uses three projectors to focus the R, G and B components onto a screen. This projector can focus its energy onto a large rear projection screen which now becomes the input monitor of our ODD. The energy from the rear projection screen is now reflected off of a mirror and a real image is formed, see Figure 22. If the rear projection screen has the same radius of curvature as the mirror the final image should be free from the effects of curvature of field. The mirror

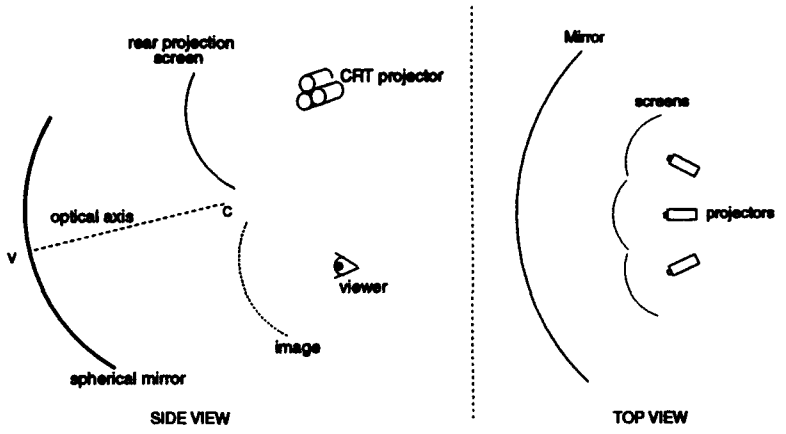


Figure 22. Large display ODD using rear projection screen and CRT projector

could be anamorphic (a different radius of curvature horizontally than vertically). A mirror which covered a very wide horizontal span could be produced so that several CRT projectors could be integrated to produce a panoramic view. Each projector would generate the appropriate view for that field, the views would join at their edges when reflected off the mirror providing a very wide field of view without loss of resolution.

3.5 Using Silicon Graphics Output on the Optical Display Device

A primary goal of this research is to determine what techniques enhance the three-dimensionality of the graphics processed through the ODD. The Silicon Graphics Workstation was selected as the system for generating graphics to be tested on the ODD. Several programs highlighting the capabilities of the Silicon Graphics were investigated. A program called ***flip*** was selected as the primary graphic program for evaluating the ODD. The graphic generated by this program is the Silicon Graphics logo and is shown in Figure 23. It is a cube shape and can be rotated and translated interactively. It provides several lighting and color options, and it incorporates many of the depth cues discussed in chapter two.

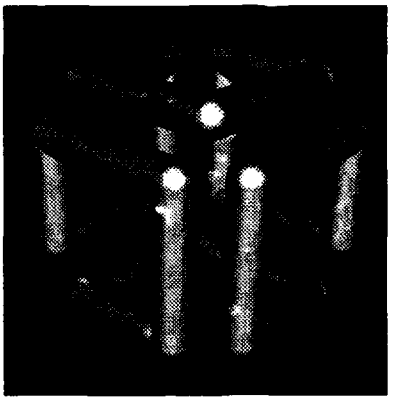


Figure 23. Silicon Graphics logo used in experimentation

A cube shaped object was selected because the perspective projection of a rotating cube provides several types of information. There is a series of different projections as the cube rotates. This is supplemented by the motion effect, in which the maximum linear velocity of points near the center of rotation is lower than that of points distant from the center of rotation. This distance can help clarify the relative distance of a point from the center of rotation. Also, the changing sizes of different parts of the cube as they change distance under perspective projection provide additional cues about the depth relationships. According to Foley, motion is most powerful when it is under the interactive control of the viewer. By selectively transforming an object, viewers may be able to form a hypothesis regarding the object more quickly (8). With this in mind the cube will be able to be translated by the viewer using a mouse or spaceball.

The TV monitor in the ODD is driven by the standard NTSC format signal. The Silicon Graphics output must be converted from its 60 Hz signal to NTSC format in order to drive the TV monitor with the Silicon Graphics output. This is accomplished using a program called *setntsc* included in Appendix A. Appendix A also discusses how to connect the Silicon Graphics video output to a TV monitor us-

ing an encoder. Once *setntsc* is executed anything generated on the Silicon Graphics can be sent to the ODD.

The *flip* program had to be modified to be used with the ODD. The most important modification for any graphic routine viewed on the ODD is that it must be inverted. Recall from Table 3, any object located between ∞ and f of a concave spherical mirror will produce an inverted image. Inverting the graphic is accomplished by rotating the graphic 180° about the x-axis (recall coordinate system in Figure 4). Figure 24 is a picture of the logo at the ODD.

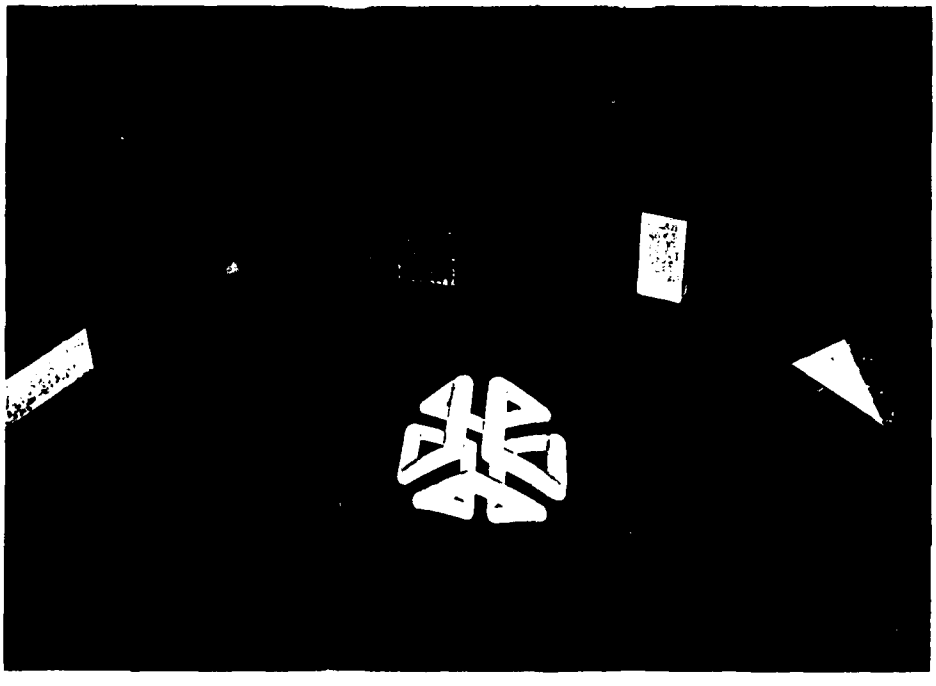


Figure 24. Logo as viewed from the ODD

Although the logo did appear to be centered in the glass viewing screen, it did not appear to be above the surface of the glass. Since the fluorescent blocks at the edge of the glass viewing plane produce strong reflections off the glass, the next step was to graphically produce a reflection of the logo. The intent of this step was to fool the eye into placing the graphically produced reflection in the same plane as the real reflection of the fluorescent blocks.

In order to create the reflected version of the graphic, the original graphic had to be reflected about the xz-plane. This is not a simple rotation about the x-axis. In a reflection through the xz-plane, only the y coordinate values of the objects position vectors change. In fact, the y values are reversed in sign as shown in Figure 25. Additionally, the lights illuminating the object had to be reversed.

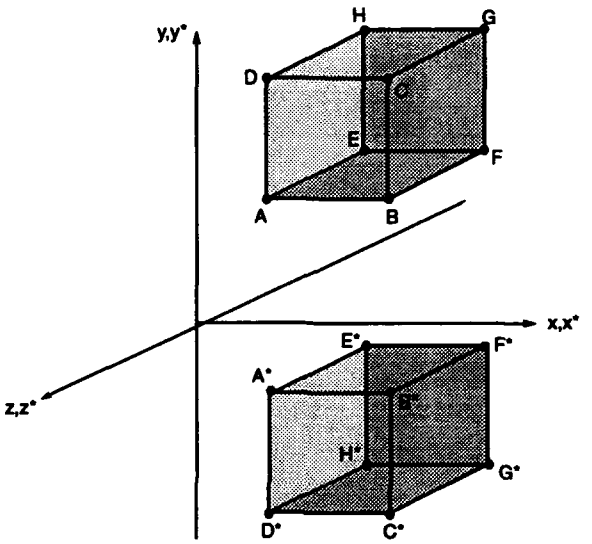


Figure 25. Reflection about the xz plane (24)

If a light was located at (x, y, z) for the original object, it must be repositioned to $(x, -y, z)$ for the reflected object. The techniques for producing the reflection of an object on the Silicon Graphics Workstation is presented in Appendix B.

A picture of the logo with its reflection as viewed from the ODD is shown in Figure 26. This accomplished the desired effect of locking the reflected image of the logo in the same plane as the reflection from the fluorescent blocks. In doing this the image of the logo appears to be above or at least standing on the surface of the glass. The problem with this view was that the reflection was too intense and the perspective was not correct. The logo and its reflection could be interpreted as two logos, one on top of the other. Decreasing the intensity of the reflection and

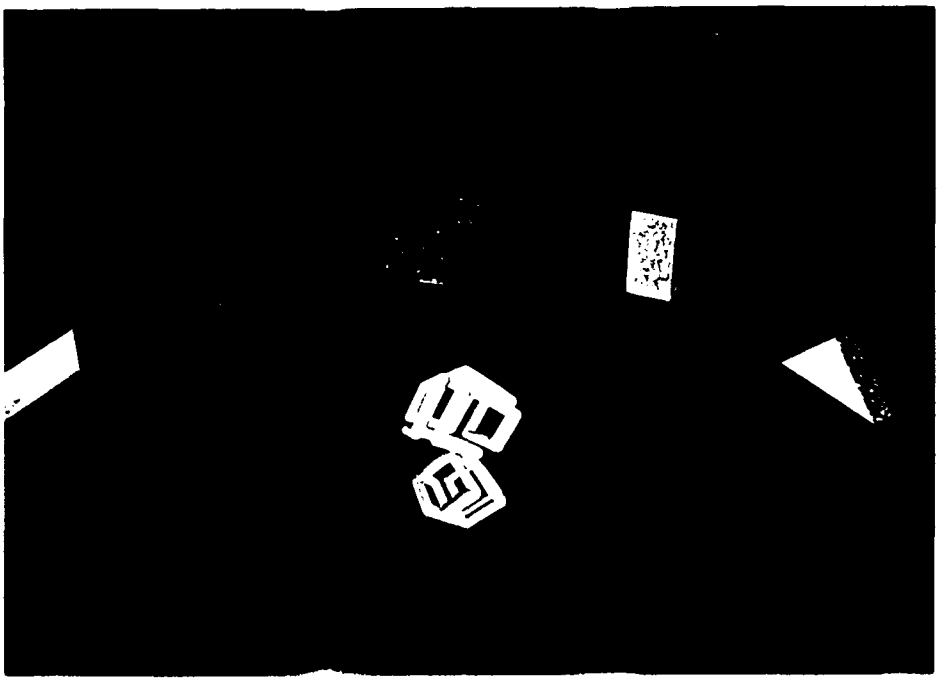


Figure 26. Logo with reflection as viewed from the ODD

scaling it down in size helped eliminate these problems. Figure 27 is a picture of the improved reflection as viewed from the ODD.

A disadvantage of this technique is the clutter a reflection adds to the screen. The screen fills up twice as fast since every object has its corresponding reflection. A screen would quickly become too cluttered to accurately interpret. Extraneous detail would have to be cut out of the scene for this technique to be effective. Often this extraneous detail provides additional depth cues that would be valuable in three-dimensional imaging. Additionally, for applications such as flight simulators or C^3I displays a reflected image is not appropriate, you don't always want things standing on mirrors.

The next technique implemented removed the reflection and added a shadow of the logo. The xz-plane was colored so that a black shadow could be seen on this plane. The graphic techniques for creating realistic shadows of objects on flat surfaces is presented in Appendix B. Figure 28 is a picture of the logo with its shadow as viewed from the ODD. This procedure required the mask on the glass viewing

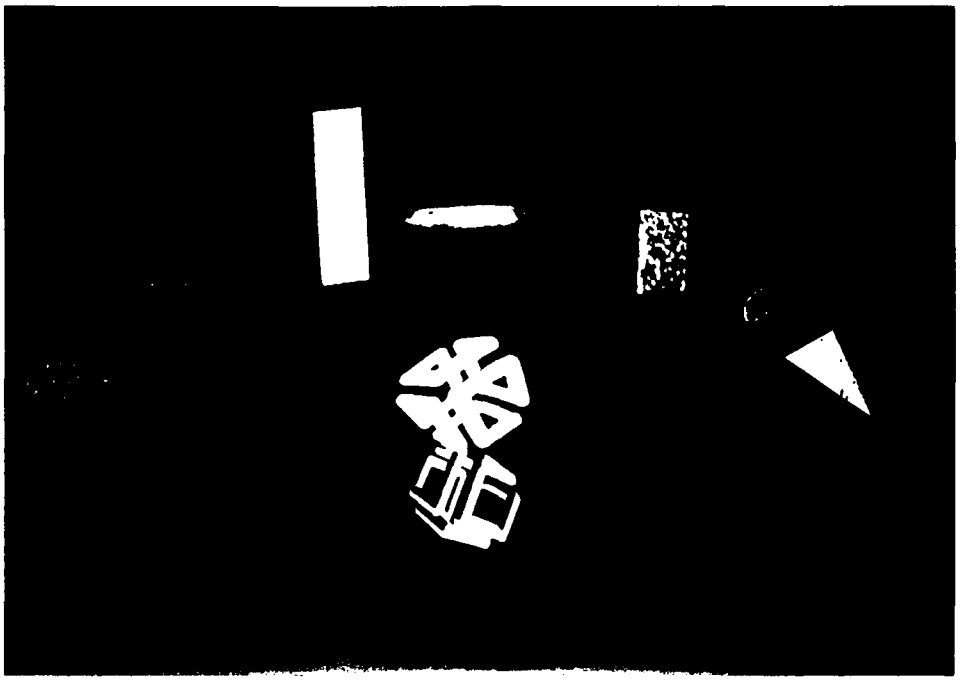


Figure 27. Logo with improved reflection as viewed from the ODD

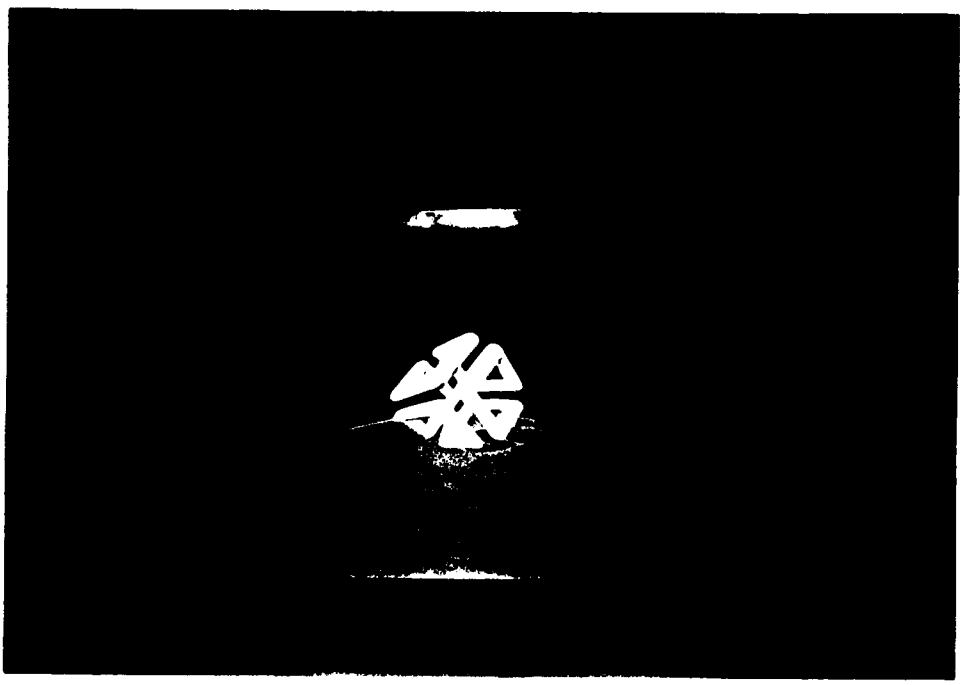


Figure 28. Logo with shadow as viewed from the ODD

surface to be pulled in to the point that the edge of the mask was flush with the image of the edge of the TV screen. This mask then couples with the image of the colored xz-plane on the monitor and lifts it to the surface of the glass, thus extending the xz-plane across the total surface of the glass viewing plane. This produced the most realistic view of the logo floating above the glass viewing plane. Additionally, a real block was placed on the viewing screen at the edge of the mask and its shadow was generated graphically on the screen. Finally, a block was generated graphically near the other edge of the screen, its shadow began on the screen and was completed by physically drawing the rest of the shadow on the glass viewing screen mask. Figure 29 is a picture of the logo with its shadow and the two shadowing techniques mentioned

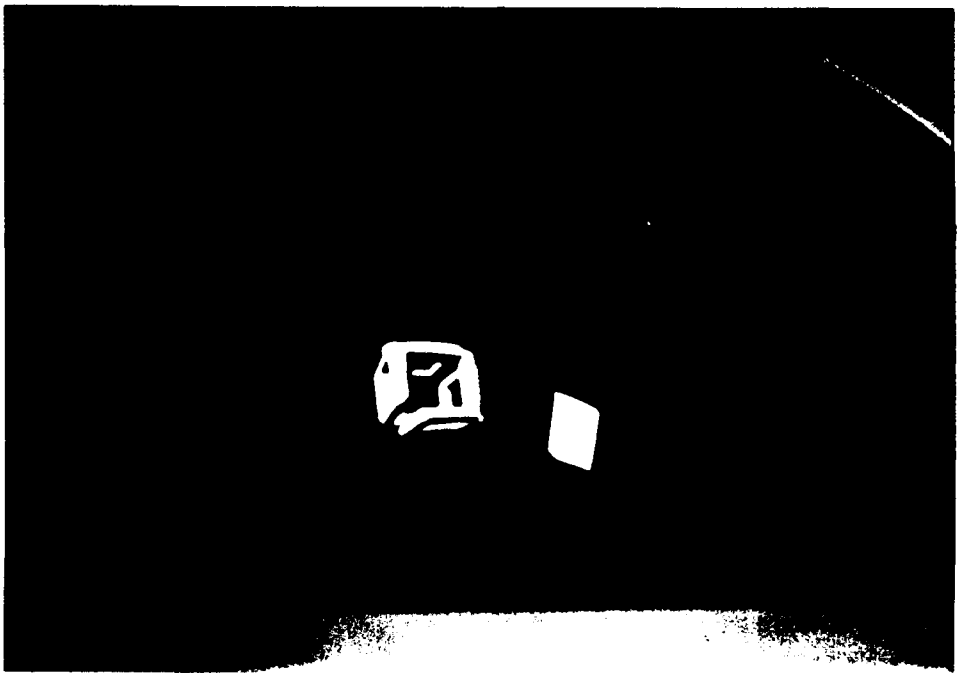


Figure 29. Logo with shadowing techniques as viewed from the ODD

above. By looking at Figure 29 the problems associated with field curvature analyzed in Section 3.3.2 are apparent. The orientation of the shadows indicates that all of the objects are not being illuminated by the same light source when in fact they are. The field curvature causes the shadow on the left block to be falling away from the viewer, the shadow of the logo is in the correct orientation and the shadow of the

right block appears to be falling toward the viewer. This can be corrected optically by reducing the amount of field curvature as suggested in Section 3.4 or graphically by forcing the shadow to different positions so they look correct at the ODD.

The final graphic experiment involves assessing how well depth is perceived on the ODD. Another logo was generated and scaled down in size. This logo was then moved in a circle around the larger logo in the center of the screen. As the smaller logo changed depth going around the larger logo the various graphic techniques discussed in chapter two were used to enhance the depth perception. The primary depth cue on the Silicon Graphics monitor was the scaling in size as the logo went further away from the viewer and occlusion as the logo went behind the larger logo. This works well for perceiving depth on the two dimensional monitor. When displayed through the ODD the viewer receives the same cues. The depth perception is enhanced however because now the viewer not only interprets the small logo as going further into the depth field but also physically can reach out and point to the space where the small logo is located. The viewer will reach further into the image space to touch objects that are further away in the depth field. Of course there is nothing there to touch and once the viewer reaches the point where the image appears he gets no tactile feedback and the effect is lost but it does give a physically measurable depth that the viewer sees the image at. Figure 30 shows the graphic used in the depth experiment.

3.6 Conclusion

This chapter focused on the optical parameters of the ODD and on the graphic techniques used to improve the three-dimensional perception at the ODD. From the optical analysis it was shown that field curvature is the primary image degrading aberration. By increasing the radius of curvature of the mirror this aberration can be greatly reduced. Furthermore, the addition of an aperture in front of the mirror and positioning the CRT at the center of curvature of the mirror increases the final

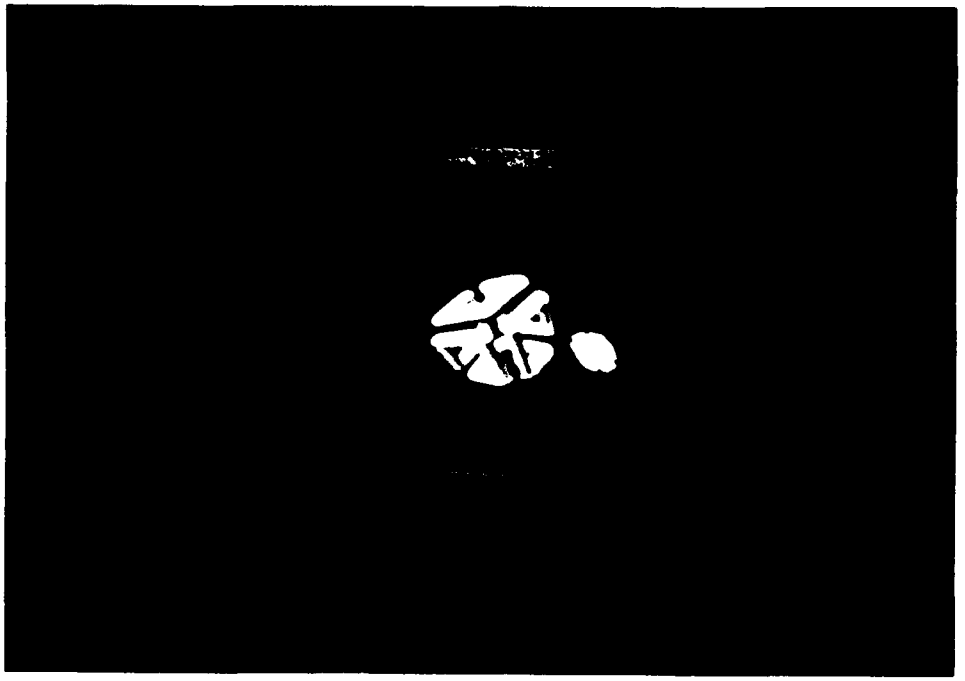


Figure 30. Depth perception graphic as viewed from the ODD

image size without degrading the image. It was also shown that the floating effect, which is key to the three-dimensional perception, would be enhanced by using a mirror which extends above the glass viewing plane so that the viewer could look down the optical axis of the system.

The graphics work demonstrated that objects generated with the standard depth cues on the Silicon Graphics appear more three-dimensional when viewed at the ODD due to the floating effect. The three-dimensional perception is enhanced by generating a reflection of the object. The reflection is referenced to the glass viewing plane and the actual object appears to rise above this plane. The three-dimensional perception is further enhanced by adding a horizontal plane (ground plane) and graphically generating the shadows cast by the objects onto this plane. This shadow technique suggests that the ODD can be used as a C^3I display. The horizontal plane is the terrain, the objects are various battlefield assets and the shadows they cast adds to the realism of the display by improving the three-dimensional perception of the objects.

Chapter 4 discusses the integration of the optical device with other research efforts going on at AFIT. The integration involves two separate research projects; one incorporates binaural sound with the display, the other incorporates terrain maps with the display.

IV. Device Integration

4.1 Introduction

This chapter discusses the integration of the ODD with other research being accomplished at AFIT. Two research projects in particular were integrated into the ODD. One project involved binaural sounds. The integration focused on coupling a graphic viewed on the ODD with the appropriate binaural sounds for the graphic being viewed. The other project involved combining several pictures of a terrain into one large map view. The integration focused on bringing these terrain images up on the Silicon Graphics and processing this through the ODD.

4.2 Binaural Sound Integration

The research in binaural sound was carried out by Capt Eric Scarborough. His thesis "Enhancement of Audio Localization Cue Synthesis by Adding Environmental and Visual Cues", discusses the sound portion of this integration effort (25). Binaural sound, or two ear sound, refers to having a separate audio signal presented to each ear. This is how audio information arrives at our ears naturally. The spectral shape of each signal and differences in the two signals are used to give a listener information about the direction and distance of sounds as well as information of the environment from which the sound originated.

Scarborough used an audio localization cue synthesizer, called DIRAD (DIRectional Audio Display), developed at Armstrong Laboratory in his research (17). This synthesizer is able to independently position two audio channels in both azimuth and elevation. This system communicates with the host computer via a RS-232 interface. In this case the host computer is a Silicon Graphics workstation . The graphic displayed at the workstation includes a man standing in the middle of the screen and at least one other graphic that visually represents the sound source. For example

a helicopter graphic corresponds to the helicopter sound that is input into the synthesizer. The helicopter can move around the man in both azimuth and elevation. The angles between the graphics man and the helicopter are sent to the synthesizer. The synthesizer uses the angles to spatially position the audio input. This is accomplished by filtering the audio with stored filters based on the outer ear (these filters are commonly referred to as the head related transfer function, HRTF) and by applying a time delay based on the source location. The synthesizer has a processor that computes the difference in angle between the desired source (helicopter) and the subjects head position (graphic man). This angle is used to calculate the time delay and distance of the source to the subjects left and right ears. For more information on the signal processing aspects of the synthesizer consult Scarborough's thesis (25). A viewer sits in front of the terminal wearing the headphones. The sound the viewer hears is the helicopter sound as referenced to the graphical man. As the graphical representation of the helicopter changes position the sound correspondingly changes to represent the sound coming from the new location.

This configuration worked well in providing both visual and aural feedback. The difficulty came in interpreting sound elevation. The ability to resolve elevation based on just aural cues is very limited (25). Coupling the aural and visual feedback enhances the human resolution capability. The visual elevation of the helicopter when viewed on a flat monitor is difficult to discern especially when the helicopter is deep in the visual field (approaching ∞).

The ODD is able to provide better depth resolution as demonstrated in Section 3.5. By coupling the graphics used in Scarborough's work with the ODD the visual elevation of the helicopter is easier to discern, especially in the far field. The changes made to the graphics include inverting the graphic so that it appears in the correct orientation at the ODD and adding a shadow of the man and the helicopter (or whatever visual is being displayed). A limitation of the visual feedback this setup provides is the field curvature aberration discussed in Section 3.3.2. As the helicopter

takes a circular flight around the graphical man, the effects of field curvature cause the helicopter to dip down slightly in the elevation field as the helicopter moves toward the far edges of the display. This effect would be greatly reduced by increasing the curvature of the mirror as discussed in the section on scaling, Section 3.4.

4.3 Terrain Map Integration

Capt Earl (USA), researched a method for creating an imagery enhanced virtual reality (IEVR) system to improve imagery intelligence support to divisional ground commanders. This method uses imagery of a battlefield coupled with a terrain model of the battlefield for the virtual reality. The imagery is collected by a number of different optical sensors which produce digitized images that can be stored in memory on a computer. The computer can manipulate each image, transforming the picture from one perspective to another. For example, software can change an image from a side view to an overhead view. By projecting the images on a terrain model the commander could view a three-dimensional photograph of the imaged area. Furthermore, using IEVR would allow him to place himself anywhere on or above this three-dimensional photograph. He could travel over the terrain and assess the enemy's strengths and weaknesses. For more information on Capt Earl's research consult his thesis "The Design and Application of an Imagery Enhanced Terrain Virtual Reality System to Support Ground Combat Commanders" (3).

The integration of IEVR with the ODD was done to see if the three-dimensional representation of the battlefield images are enhanced by using the ODD to view the scenes rather than the Silicon Graphics monitor. Additionally, the ability to add icons representing the commanders assets (tanks, troops,...) has already been shown feasible in the graphics research discussed in Section 3.5. The integration of the ODD with terrain maps demonstrates the potential this device has in the area of C^3I displays.

The terrain images used in Capt Earl's research were very dark. They consisted of images from a variety of sensors including forward looking infrared (FLIR) images. FLIR images produce white spots where hot items appear and dark spots where cool item appear. A typical battlefield FLIR image is very dark with a few white spots scattered around representing tanks, trucks, troops, ... Although someone trained in reading FLIR images can identify the various spots and categorize them, they are not the desired format for a battlefield display. Since the ODD's mirror has a very low reflectivity (Section 3.2.1) it requires very bright images to produce the desired floating effect. The terrain images used in this research were to dark to be of real value on the ODD. If the imagery could be enhanced and lightened either by using pictures from a conventional camera or by some image processing techniques, a useful C^3I display device would be realized. The graphic techniques demonstrated in Section 3.5 could be used to project icons of various hardware onto the terrain. Additionally, by integrating the dataglove with the display the commander could interact with the battlefield and his assets.

4.4 Conclusion

The ODD can be used as a tool in virtual reality. Incorporating binaural sound to the ODD allowed the interaction of sight and sound in this pseudo virtual reality. The addition of the dataglove would allow the user to physically interact with the virtual reality. The sight and sound combination aided in the elevation discrimination of sound producing objects (helicopter). The limitation optically was the problem associated with field curvature discussed in Section 3.3.2. The moving objects followed the field curvature as they moved away from the center of the display. Therefore, the viewer expects to see a straight and level flight path but due to the field curvature the flight path curves downward as the object moves toward the edge. This problem can be solved optically as discussed in Section 3.4.

The ODD was limited as a C^3I display by the quality of the imagery available. The dark IR pictures were hard to see on the Silicon Graphics workstation and even harder to see on the ODD (due to the energy loss in reflection off the mirror). A brighter picture with more contrast would show up much better on the ODD. The concepts presented in Section 3.5 of adding icons of battlefield elements along with their shadows would create a realistic battlefield environment. Furthermore, the addition of the dataglove as discussed above would allow the commander to interact with the battlefield. The concept is here but better imagery is needed.

Chapter 5 presents the major findings of this research effort and provides some recommendations for additional research.

V. Conclusions and Recommendations

This chapter summarizes the major findings of this thesis effort and provides some recommendations for additional research. The conclusions are broken into a graphics section and an optics section.

The most realistic three-dimensional image was formed on the ODD when the graphic included a horizontal plane and a shadow of the object of interest. With this technique the floating effect was most convincing. This effect was essential for producing realistic three-dimensional images. The technique of placing a real object on the mask and generating a graphical shadow for it also aided the floating effect of the graphic. Care must be taken when generating the shadows to get the proper perspective of the shadow on the display. Although the shadows appear in the correct orientation on the Silicon Graphics display the field curvature on the ODD will cause the shadows to have the incorrect position with respect to the light source.

The reflection technique also caused the graphic to float above the glass viewing plane but not as well as the shadow method. Additionally, the reflection takes up more screen space, although this is not a problem when just one object is being displayed the screen would become cluttered and confusing as more objects and their reflections are added.

The ODD also demonstrated that depth perception is improved because the viewer not only interprets the depth cues that indicate the image is further into the depth field but also physically can reach out and point to the space where the image is located. The viewer will reach further into the image space to touch images that are further away in the depth field. Of course there is nothing there to touch and once the viewer reaches the point where the image appears he gets no tactile feedback and the effect is lost but it does give a physically measurable depth that the viewer sees the image at.

The dynamic motion of the graphic also increased the realism of what was being displayed. As the graphic is rotated and translated in a realistic manner, a series of different projections of the object are presented to the viewer improving the depth perception. When adding motion with the reflection of the object, the horizontal plane (ground plane) must be treated as like a mirror. The object cannot go below this plane and the refiection cannot go above it. As the object moves upward from the horizontal plane, the reflection must move down. The shadow effect under motion provides a similar realism. Additionally, the shadow technique, outlined in Appendix B produces the correct shadow of the object regardless of the position or orientation. This is another benefit of using the shadow method.

A comparison of the key optical parameters of Echeverry's device, the ODD and the scaled ODD are presented in Table 6. The optical analysis showed that

Table 6. Results comparison

Device	IFOV	Exit Pupil	Petzval Curve	Mag	Res	Viewing Window
Echeverry	±1.38°	6 cm	0.0008 cm	1	N/A	15°
ODD	±6.06°	43 cm vert 65 cm horiz	0.047 cm	.558	42.6 pixels/deg	73°
Scaled ODD	±10.4°	73 cm vert 65 cm horiz	0.033 cm	1	61.44 pixels/deg	73°

the instantaneous field of view was improved over the display that Echeverry used. The instantaneous field of view of the scaled ODD approaches the typical field of view of operational helmet mounted displays (28). Additionally, the exit pupil of the ODD is greatly enlarged over Echeverry's system allowing for multiple viewers to simultaneously view the display. Echeverry's display allowed one viewer to view the display in a 15° viewing window. The ODD can comfortably allow 5 viewers to see the display simultaneously in a 73° horizontal viewing window. The aberration analysis showed that field curvature was the primary visual image degradation factor. With

some clever graphics techniques this curvature effect can be minimized. Additionally, by increasing the radius of curvature of the mirror and adding an aperture in front of the mirror the aberration effects are greatly reduced. Finally, by moving the monitor closer to the mirror a larger display is achieved.

The integration of the ODD with applications involving binaural sound demonstrated the potential for this device to be used as a tool in investigating virtual realities. Although a true virtual reality display will require a much larger instantaneous field of view, the improved depth perception offered by the ODD demonstrates the enhancement a three-dimensional display will provide a virtual reality system. Finally, the ODD could be integrated with a dataglove to allow interaction with the virtual environment.

The integration of the ODD with terrain maps demonstrates the potential this device has in the area of C^3I displays. The terrain images used in this research were too dark to be of real value on the ODD. If the imagery could be enhanced and lightened either by using better pictures to begin with or by some image processing techniques, a useful C^3I display would be realized. The graphic techniques demonstrated in this research could be used to project icons of various hardware onto the terrain and by integrating the dataglove as mentioned in the previous paragraph, the commander could interact with the battlefield and his assets.

Appendix A. *NTSC Output from Silicon Graphics Workstation*

A.1 Changing the Silicon Graphics output using an encoder

To change the graphics display from the Silicon Graphics to the TV monitor you must change the video signal from a 60 Hz signal which drives the Silicon Graphics monitor to a NTSC signal which drives a standard TV monitor. There are two C programs which do this on the Silicon Graphics. To go from Silicon Graphics format to NTSC use the program called setntsc. To go from NTSC to Silicon Graphics use the program called set60. These programs are listed at the end of this appendix or on the Silicon Graphics in the following directory *~/amburn/src/sgi/misc.* Once these programs are compiled they can be invoked by typing *set60* or *setntsc.* When you are on the Silicon Graphics and you type *setntsc* the screen will go to noise. By typing *set60* you will return the display to its normal format. It is important to note that the window the mouse pointer is in when you type *setntsc* is the same window the mouse pointer must be in when you type *set60.* You will not be able to see the mouse pointer or what you are typing on the screen once the *setntsc* command has been invoked.

To view the Silicon Graphics output on the TV monitor you must use the Silicon Graphics 4D workstation named Michelangelo. Michelangelo is connected by an A/B switch (sitting on top of the workstation) to an encoder labled ENC VI. It is a deep wide but thin box that sits next to the TV and is made by Lyon Lamb. The front of the encoder has several swithces, see Figure 31. The far left switch is power and the next switch to the right should be in the EXT position.

The back of this box has several coaxial cable connections, see Figure 32. The 4 cables from the Silicon Graphics (red, green, blue, and sync) plug in the back. The switch for each of the cables should be in the 75 ohm position. The far right as viewed from the back contains two video out ports. The TV monitor is connected by coaxial cable to a video out port.

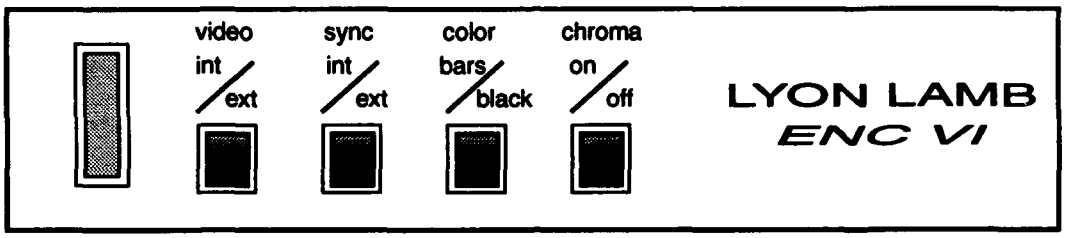


Figure 31. Front panel of encoder

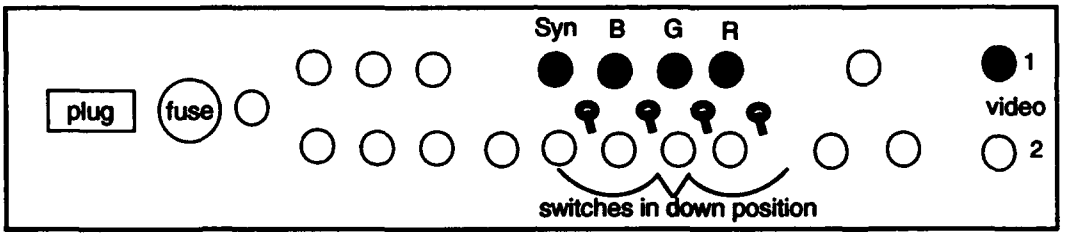


Figure 32. Back panel of encoder

Only the lower left quadrant of the Silicon Graphics screen will be seen on the TV monitor. This is important to remember when sweeping out your viewing window on the Silicon Graphics. Start your window about half of the way up the left side of the screen and sweep down to about half way across the bottom of the screen. This will ensure the graphic you see on the Silicon Graphics will be seen on the TV monitor. The actual Silicon Graphics screen is 1280 by 1024 pixels, the portion sent to the TV monitor is 643 by 485 pixels.

A.1.1 Step by step procedure

1. Ensure the encoder is hooked up properly (see Figures 31 and 32 above), power is on, and the first switch is in the EXT position.
2. Bring up two shell windows on the Silicon Graphic (Michelangelo), one in the lower left the other in the upper right.
3. In the lower left window call up your graphic program you wish to display.

4. Sweep out the window as discussed above.
5. Move cursor into upper window and type *setntsc*, the screen should go to noise at this point.
6. Set A/B switch sitting on top of workstation to B, the graphic should now appear on the appropriate TV monitor.
7. To return to Silicon Graphics display change the A/B switch to A and (assuming you have not moved the cursor out of the upper right window) type *set60.*

A.2 Using the IRIS 4D 440/VGXT Silicon Graphics Workstation

The 440/VGXT provides an easier way to send the Silicon Graphics output to the TV monitor. The job of the encoder and A/B switch described above is all handled internal to the workstation. The coaxial cable connected to the TV monitor is connected to the composite video encoder output connector located behind the front panel of the workstation. Once this connection has been made sweep out the window of interest and use the *setntsc* and *set60* commands as described above.

One additional feature the 440/VGXT has is a broadcast video option (BVO). The BVO is typically used to make video tapes from the Silicon Graphics, however, it has other features that can be use to improve the appearance of Silicon Graphics output sent to a TV monitor. The most useful feature for this thesis effort is the color bar pattern that BVO generates. The command *bvo_pat* generates the standard color bar pattern in the lower left quadrant of the Silicon Graphics screen. This can be sent to the TV monitor using *setntsc*. The command *bvo_admin* generates a user interface screen that allows the user to select and adjust various functions of the BVO.

A.3 Programs for changing Silicon Graphics output

A.3.1 set60

```
#include <gl.h>
#include <get.h>

main ()
{
    ginit ();
    setmonitor (HZ60);
    greset();
    gexit ();
}
```

A.3.2 setntsc

```
#include <gl.h>
#include <get.h>

main ()
{
    ginit ();
    setmonitor (NTSC);
    gexit ();
}
```

Appendix B. *Mathematical Methods for Making Reflections and Shadows*

B.1 Introduction

Points and the lines that join them are the core elements that are used to display graphical information. The ability to transform these points and lines is basic to computer graphics. When visualizing an object it may be desirable to scale, rotate, translate, distort or develop a perspective view of the object. All of these transformations can be accomplished using matrix multiplication. A detailed reference of these mathematical techniques is presented in David Rogers book, "Mathematical Elements for Computer Graphics" (24). This appendix presents the techniques used to create a reflected version of an object as well as to create shadows of an object on a flat surface.

The objects drawn in the graphics routines on the Silicon Graphics workstations consist of a number of polygons that when joined together form the desired object. Each of these polygons is specified by its vertices in three dimensional space $[x, y, z]$. These vertices are defined in a matrix and are called by the *bgnpolygon()* command. When this command is executed the vertices are read from of the matrix and the polygons are rendered producing the desired object. This object is now the on top of the matrix stack. The matrix stack is an area of RAM that stores in matrix representation the current graphic being displayed. This is handy because now all of the transformations can be carried out by matrix multiplication. By multiplying this matrix stack by the appropriate transformation matrix $[T]$, scaling, rotation, translation or distortion of the graphic is accomplished.

The generalized 4 × 4 transformation matrix $[T]$ for three-dimensional homogeneous coordinates is shown in Equation 4.

$$[T] = \begin{bmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ m & n & o & p \end{bmatrix} \tag{4}$$

This can be partitioned into four separate sections:

$$\begin{bmatrix} & & & \vdots & 3 \\ & 3 \times 3 & & \vdots & \times \\ & & & \vdots & 1 \\ \cdots & \cdots & \cdots & \vdots & \cdots \\ & 1 \times 3 & & \vdots & 1 \times 1 \end{bmatrix}$$

The upper left 3 × 3 submatrix produces linear transformations such as shearing, rotation, translation, scaling and reflection. The lower left 1 × 3 submatrix produces translation, and the upper right 3 × 1 matrix produces a perspective transformation. The lower right 1 × 1 submatrix accomplishes overall scaling. Obviously from one transformation matrix $[T]$ a combination of shearing, rotation, local scaling, reflection, translation, perspective and overall scaling can be accomplished (24). For example, to translate the point (x, y, z) by Dx, Dy, Dz respectively, the following matrix manipulation takes place.

$$[x\ y\ z\ 1] \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ Dx & Dy & Dz & 1 \end{bmatrix} = [x + Dx\ y + Dy\ z + Dz\ 1]$$

Note that in graphics mathematical manipulations all points and transformation matrices are represented in homogeneous coordinates. This allows all of the transformations to be done by matrix multiplication. If they were not put in homogeneous coordinates the above translation example could only be done by a matrix addition.

B.2 Three-Dimensional Reflection

In three-dimensions, reflection occurs through a plane. In the program *flip*, used in evaluating the ODD, the reflection was through the xz plane. In this reflection, only the y values of the objects position vector change. In fact, they are simply reversed in sign. The transformation matrix for a reflection through the xz plane is shown in Equation 5.

$$[T] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

For reflection through the xy plane the z component of the transformation matrix, element 3,3, is -1. Likewise, for transformation through the yz plane the x component, element 1,1, is -1.

The following example taken from Rogers book illustrates the reflection transformation graphically (24). The block $ABCDEFGH$ shown in Figure 33 has the

position vectors

$$[X] = \begin{bmatrix} 1 & 1 & 0 & 1 \\ 2 & 1 & 0 & 1 \\ 2 & 2 & 0 & 1 \\ 1 & 2 & 0 & 1 \\ 1 & 1 & -1 & 1 \\ 2 & 1 & -1 & 1 \\ 2 & 2 & -1 & 1 \\ 1 & 2 & -1 & 1 \end{bmatrix}$$

where the first row represents the homogeneous position vector for vertex A, the second row is vertex B, and so on. The transformation matrix for reflection through

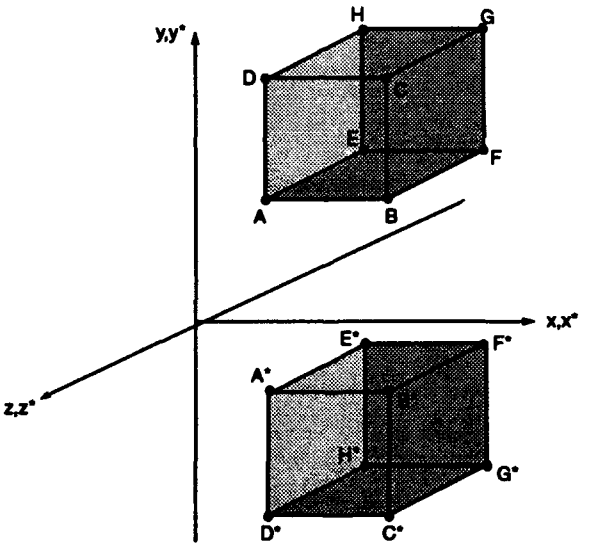


Figure 33. Reflection about the xz plane (24)

the xz plane is given by Equation 5. After reflection the transformed position vectors

are

$$[X^*] = [X][T] = \begin{bmatrix} 1 & 1 & 0 & 1 \\ 2 & 1 & 0 & 1 \\ 2 & 2 & 0 & 1 \\ 1 & 2 & 0 & 1 \\ 1 & 1 & -1 & 1 \\ 2 & 1 & -1 & 1 \\ 2 & 2 & -1 & 1 \\ 1 & 2 & -1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 & 1 \\ 2 & -1 & 0 & 1 \\ 2 & -2 & 0 & 1 \\ 1 & -2 & 0 & 1 \\ 1 & -1 & -1 & 1 \\ 2 & -1 & -1 & 1 \\ 2 & -2 & -1 & 1 \\ 1 & -2 & -1 & 1 \end{bmatrix}$$

where the first row represents the homogeneous position vector for vertex A^*, the second row is vertex B^*, and so on. The result $A^*B^*C^*D^*E^*F^*G^*H^*$ is shown in Figure 33.

B.3 Shadows for Three-Dimensional Objects

Casting a shadow of an object onto a flat surface involves projecting a two dimensional view of the three-dimensional object onto the flat surface. The line of projection is a straight line from the light source through the three-dimensional object to the surface as shown in Figure 34.

A quick way to flatten an object is to use the *scale* function and set the axis you want to flatten to zero. For example, if the xz plane is the plane on which the shadow will be cast, set the y dimension to zero, *scale*(1.0, 0.0, 1.0). The *scale* function multiplies the matrix stack (the current graphic in its matrix form) by the

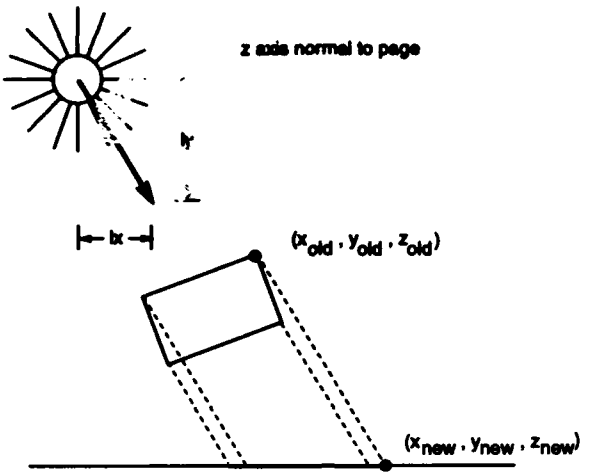


Figure 34. Shadow from an infinite light source (27)

transformation matrix shown below.

$$[T] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

This will create a realistic shadow assuming that the light source is shining straight down the y axis. The scale function alone is good only for casting shadows when the light is shining down a major axis. A series of rotations and scales could be used to cast a shadow from an arbitrary direction. A much easier approach involving a single transformation matrix is proposed by Tessman (27). Tessman creates a single transformation matrix and uses the *multmatrix* function where the *scale* function would be.

Lights in the Silicon Graphic are either infinite or local. When dealing with shadows, an infinite light source produces soft shadows while local light sources produce sharp, dark shadows. When the lights are defined in the code they are given either a infinite or local type. Consider an infinite light source, at an arbitrary

location, shining on an object and casting a shadow on the xz-plane as shown in Figure 34. The equations for casting a shadow on the ground at $y = 0$, assuming an infinite light source, are:

$$x_{new} = x_{old} + y_{old}\frac{lx}{ly}$$

$$y_{new} = 0$$

$$z_{new} = z_{old} + y_{old}\frac{lz}{ly}$$

where lx, ly and lz are the components of the light vector. The transformation matrix built from these equations is shown in Equation 6.

$$[T] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ \frac{lx}{ly} & 0 & \frac{lz}{ly} & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

If a local light source is used the notation changes so that lx, ly and lz are the absolute coordinates of the light as shown in Figure 35. The ground is at $y = 0$, therefore:

$$y_{new} = 0$$

and by similar triangles:

$$x_{new} = \frac{ly \times x_{old} - lx \times y_{old}}{ly - y_{old}}$$

$$z_{new} = \frac{ly \times z_{old} - lz \times y_{old}}{ly - y_{old}}$$

The transformation matrix built from these equations is shown in Equation 7.

$$[T] = \begin{bmatrix} ly & 0 & 0 & 0 \\ -lx & 0 & -lz & -1 \\ 0 & 0 & ly & 0 \\ 0 & 0 & 0 & ly \end{bmatrix} \tag{7}$$

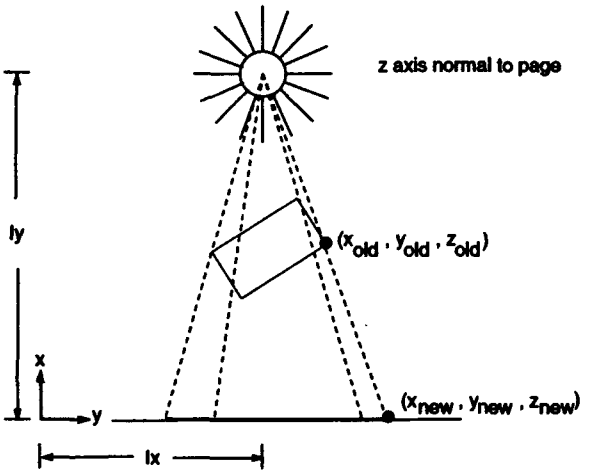


Figure 35. Shadow from a local light source (27)

Once the appropriate transformation matrix has been created the following program fragment can be used to produce the shadows for either local or infinite sources.

```
pushmatrix();
multmatrix(T);          /*the appropriate transformation matrix*/

position_object();      /*a set of rotates and translates that is normally*/
                        /*used to position and orient the object*/
```

```
draw_object_shadow();      /*the shadow version of the object should be*/
                           /*the same as the object, only black*/
                           /*(no lighting or color)*/

popmatrix();
```

Appendix C. *Code V, a Lens Analysis Program*

C.1 Introduction

This appendix discusses a software program called Code V developed by Optical Research Associates, (818)795-9101. Code V is a comprehensive computer program for the design and analysis of optical systems. It can be used to analyze a wide variety of lens systems. Some Code V's capabilities are listed in Table 7.

Table 7. Code V capabilities (11)

Surface Types	System Types	Image Evaluation	Lens Analysis
Spherical	Objectives	Spot Diagram	Lens Drawing
Cylindrical	Zoom	OPD	Weight and Cost
Aspheric	Anamorphic	Diffraction MTF	Ghost Image
Aspheric Toroid	UV/Visual/IR	Parallax	Element Drawing
Fresnel	Spectrographic	Partial Coherence	Thermal Environ
Diff Grating	Simulators	Spread Functions	Pressure Environ
Tilted	Gradient Index	Knife Edge Scan	Spectral Trans
Decentered	Coatings	Encircled Energy	Image Simulation
Holo Gratings	Fourier Trans	Laser Prop	Rel Illum

C.2 Using Code V

Code V is a very powerful analysis program. Along with the power comes the associated frustrations of learning a new software program. Unfortunately, at AFIT the frustration is compounded due to the fact that there is not a DEC VT125 or VT240 computer for student use. Although many of the computers available for student use have the correct emulators, they do not function like the Code V manual indicates they should. This section is written to point out some of these pitfalls.

This program is an optical diagnostic tool and is available on the VAX computer, CSC. It is extremely useful in evaluating aberrations associated with an optical

system. Code V must be provided with the lens system before it can do any analysis. A system is entered in terms of the distances a light ray travels along the optical axis form the object plane through the various lenses to the image plane. Additionally, the refractive indices and the surface curvatures of the lenses the light rays travel through must be provided when defining the lens system.

Although Code V has an easy screen entry system that allows the lens system data to be entered without learning a bunch of commands, this requires a DEC machine. The DEC machines that Code V is designed to run on has a "gold key" that allows the user to move around from screen to screen, inputting and changing the data. The gold key equivalent on both the NEXT computers and the Sun Workstations does not produce the same results. In particular, saving data input by the screen method was not possible. The unfortunate result is that the user must learn the command mode method of getting around Code V. There is a prompting guide available from the Physics Department that lists all of the commands with a brief synopsis of what they do. This guide is a must. Additionally, the Physic Department has the reference manuals and a introductory guide that are essential for getting started on Code V.

To get started, logon to CSC and type *CV7/com*. This opens Code V in the command mode. Entering a lens system is best accomplished by getting the reference manual from the Physics Department and following the "Defining a New Lens" users session in section 1-B. This goes step by step through the commands required to enter a system and shows how to check to see that everything was entered correctly. Once a lens system is entered, the command *DRA* (draw) will draw the lens system. This is a quick way to check if the lens system was entered correctly. Note, any graphics output, such as the results of *DRA*, requires a graphics emulator. On the NEXT computers there is not a compatible graphics emulator. To get good graphics results from Code V use the Sun Workstations.

Another handy command is *LIS* (list). This lists all of the specifications of the current lens system starting with the object plane and working its way element by element to the image plane. This is an easy way to keep track of where the various elements are positioned and the parameters of each element.

A list of all the commands would be fruitless as there are literally thousands. The most useful commands are application specific and are easily found in the manuals under the application desired. The manuals have step by step examples for each application. After going through the appropriate examples, the commands are fairly easy to remember or at least look up in the prompting guide. The commands for saving a file, restoring a file, and exiting the program are probably the most used and are listed below.

- *SAVfilename* -saves the file.
- *RESfilename* -restores a previously saved file.
- *EXIT* -exits the program.

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Vita

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This thesis investigates a technique for improving the perception of three-dimensionality in images generated by a Silicon Graphics workstation. The technique involves using a spherical mirror into which the graphics from the CRT are projected. A real image of the graphic is formed by the mirror and it appears to be floating at the image plane. The three-dimensional effect is improved by adding reflections or shadows of the displayed object. Additionally, a method of using real objects with computer generated shadows and computer generated objects with real shadows is investigated. This is done in an effort to quantify how far the real world can be integrated with the display as well as to show that the three-dimensionality of the original graphic is enhanced. The optical system is analyzed to show where the images are being formed and to determine the aberrations present in the system. The most noticeable image degradation is due to curvature of field. An improved optical system is proposed that would reduce this effect and increase the size of the display. Finally, this optical device along with the graphic techniques are integrated with two other research efforts. The first integration involves research in binaural sound and focuses on coupling visual and aural cues to create a pseudo synthetic environment. The second integration effort introduces battlefield terrain images into the optical device to enhance the images and functions as a C^3I display.

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3-D imaging, synthetic environment, virtual reality, non-coherent display	**90**
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UL**